Photometric Redshifts and the Luminosity-Size Relation of Galaxies out to $z = 1.1$

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Abstract. Photometric redshifts are now established as a mature and reliable tool, and the emphasis is shifting to the exciting science they can produce especially in the era of new, large format CCD mosaics. In the spirit of showing the potential of photometric redshifts for large surveys of distant galaxies, this contribution first analyzes the luminosity-size relation of galaxies out to $z = 1.1$ using a set of Keck Telescope redshifts from the DEEP survey. The same analysis is then repeated solely with photometric redshifts. Both analyses yield the same result: the central surface brightness of high-redshift galactic disks does not significantly increase out to $z = 1.1$ when selection effects are taking into account. Given that reliable photometric redshifts can be obtained for thousands and thousands of galaxies in just a few nights of imaging, they offer a powerful and economical way to increase current galaxy redshift samples by at least an order of magnitude.

1. Introduction

Since individual galaxies cannot be observed at different epochs, distant galaxy evolution can be operationally defined as the statistical change in galaxy properties with redshift. Correlations between observables such as total absolute magnitude M, half-light radius R_{hl}, disk scale length R_d, and rotation speed V_c are particularly powerful diagnostics, as they involve key global properites of galaxies, namely luminosity, size and mass. Semi-analytic models of galaxy formation and evolution can now make testable predictions regarding these fundamental galaxy parameters and their associated scaling relations.

Understanding the luminosity-size scaling relation would benefit tremendously from large galaxy redshift samples based on reliable photometric redshifts collected with large format CCD mosaics (e. g. the CFHT 12k Camera). This contribution directly compares the luminosity-size relation of distant galaxies over the range $0.1 \leq z \leq 1.1$ measured from Keck and photometric redshifts.

2. Galaxy Scaling Relations: Tests of Galaxy Evolution

Schade et al. (1996a,b) pioneered the luminosity-size relation of distant galaxies and found that the late-type galaxy luminosity-size relation showed an apparent increase in disk surface brightness of ~ 1 mag at a given R_d by $z = 0.6$, both in the outer regions of clusters and in the field. Similarly, the effective surface brightness of early-type galaxies seemed to increase by 0.7 mag at $z = 0.6$. Roche et al. (1998) studied the surface brightness and size of 270 *HST* galaxies out to $z = 4$ taken from various redshift surveys. They found that the mean rest-frame blue-band surface brightness at a fixed radius seemed to increase smoothly by 0.95 mag between $z = 0.2$ and $z = 0.9$. Finally, Lilly et al. (1998) measured an increase with redshift of 0.8 ± 0.3 mag in the surface brightness of large ($R_d > 4h_{50}^{-1}$) disks.

The question of whether the apparent evolution seen in galaxies at high redshifts is operating in both luminosity and/or size has received considerable attention in a recent flurry of theoretical activity aimed at explaining the formation and evolution of disk galaxies (Bouwens, Cayón, & Silk 1997; Dalcanton, Spergel, & Summers 1997; Mo, Mao, & White 1998). Certain semi-analytic no-infall models predict that disk scale length should vary as $(1+z)^{-1}$ in an $\Omega = 1$ universe whereas infall models predict a milder disk size evolution. Disk sizes at $z \sim 1$ in these models are typically only 20% smaller than at $z = 0$. Disk size is therefore important by itself to distinguish between these different scenarios even though, as pointed out by Mao, Mo, & White (1998), it is likely that only kinematic information can decisively separate evolution in the mass and size of galaxies from evolution in their stellar mass-to-light ratio.

3. The DEEP Groth Strip Survey Sample

3.1. *HST* Structural Parameters

The *HST* data are from two surveys, which we dub the "Groth Survey Strip" (GSS), taken under *HST* programs GTO 5090 and GTO 5109. The GSS consists of 28 overlapping WFPC2 subfields, and each of 27 subfields has exposures of 2800 s in the broad V filter ($F606W$) and 4400 s in the broad I filter ($F814W$). The 28th field is the Deep Field (J2000 1417.5+52.5), with total exposures of 24,400 s in V and 25,200 s in I. The images were recalibrated "on-the-fly" through the Canadian Astronomy Data Center (CADC) standard pipeline and coadded with IRAF. Structural parameters were measured by fitting the surface brightness profiles of galaxies in the DGSS sample with a PSF-convolved de Vaucouleurs bulge + exponential disk 2D model (GIM2D: Simard 1998, Marleau & Simard 1998).

3.2. Keck/LRIS Spectroscopy

GSS galaxies with $(V + I)/2 < 24$ are currently being systematically surveyed by the DEEP team using the LRIS multi-object spectrograph on the Keck II Telescope. Spectra of a first group of 231 galaxies were acquired between May 1995 and May 1997, and these are the galaxies used here. The total spectral coverage was about 4500–9100 Å, and the typical total exposure time per target field was 5400 seconds. The final DGSS sample has a total of 217 objects with both Keck redshifts and *HST* structural parameters. The sample was cut down further to 190 galaxies by selecting only galaxies brighter than $I_{814} = 23.5$. The DGSS redshift sample is 100% statistically complete down to $I_{814} = 23.5$.

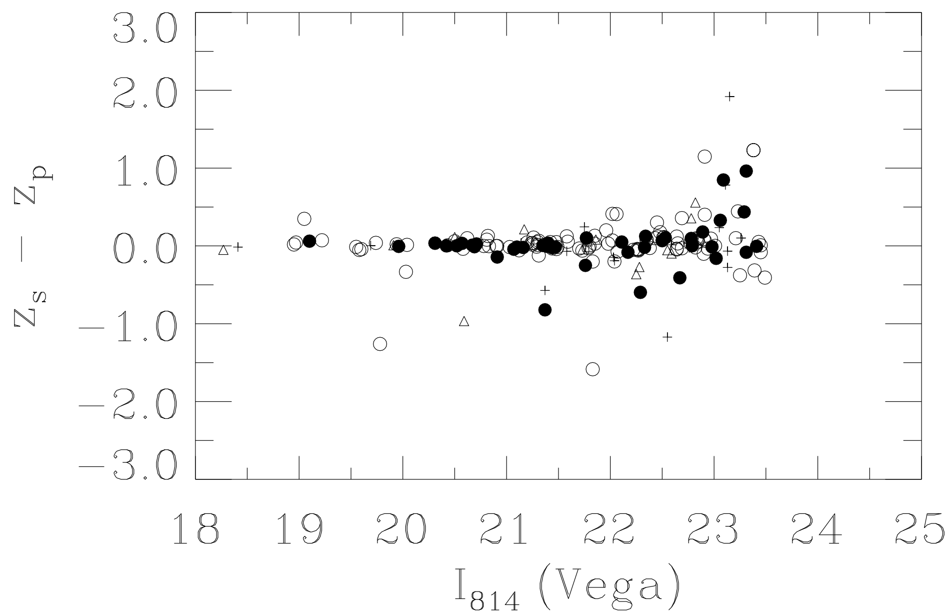

Figure 1. Comparison between DGSS photometric and Keck spectroscopic redshifts as a function of galaxy total I_{814} magnitude and bulge fraction B/T for 188 galaxies in the DGSS sample with both spectroscopic and photometric redshifts (*Open circles:* $0.00 \leq B/T < 0.25$, *Filled circles:* $0.25 \leq B/T < 0.50$, *Pluses:* $0.50 \leq B/T < 0.75$, *Triangles:* $0.75 \leq B/T < 1.00$). The difference between z_p and z_s is primarily a function of total magnitude.

3.3. Photometric Redshifts

Imaging data for the DGSS photometric redshifts were acquired in April 1995 using the Prime Focus CCD (PFCCD) camera on the Mayall 4m telescope at Kitt Peak National Observatory. Total exposure times were 30000 s in U, 15900 s in B, 4500 s in R, and 4200 s in I. Photometric redshifts were measured by R. J. Brunner using the procedure described in Brunner et al. (1997). Figure 1 shows a comparison between Keck and photometric redshifts as a function of total galaxy magnitude and bulge fraction B/T. There is no systematic trend in the difference $z_s - z_p$ with bulge fraction. Furthermore, no systematic trends in $z_s - z_p$ were seen with total galaxy residual flux from the fitting model, rest-frame $B - V$ galaxy color and intrinsic half-light radius R_{hl}.

4. Surface Brightness of High-Redshift Disks

4.1. Selection Effects

The observed distribution of galaxies in the $M_{B_0} - R_d$ plane as a function of redshift $\Psi(M_{B_0}, R_d, z)$ is the result of any inherent changes in the resident galaxy distribution $\Psi_U(M_{B_0}, R_d, z)$ in that plane and of observational selection effects.

The term "resident" here to refer to the intrinsic galaxy population at a given redshift z. In the absence of real evolution in the galaxy population with redshift, all resident populations would be the same as the local population of galaxies. Selection effects are likely to be significant given the wide range of sizes and surface brightnesses observed locally. It is therefore important to carefully characterize selection effects to disentangle them from real changes in $\Psi_U(M_{B_0}, R_d, z)$. The path from $\Psi_U(M_{B_0}, R_d, z)$ to $\Psi(M_{B_0}, R_d, z)$ is given by:

$$\Psi(M_{B_0}, R_d, z) = S_{PS}(M_{B_0}, R_d, z) S_{UP}(M_{B_0}, R_d, z) \Psi_U(M_{B_0}, R_d, z), \tag{1}$$

where M_{B_0} is the rest-frame B-band absolute magnitude, and R_d is the disk scale length in kpc. The subscript UP stands for "Universe to Photometric sample", and the subscript PS stands for "Photometric sample to Spectroscopic sample". The resident galaxy distribution $\Psi_U(M_{B_0}, R_d, z)$ is not known *a priori*. Once the two selection functions in Equation 1 have been characterized, their product (denoted S_{US} hereafter) shows the region of the $M_{B_0} - R_d$ plane where real galaxies would have been observed if they existed in that region at high redshift. Detailed derivations of the selection functions are given in Simard et al. (1999).

4.2. DGSS Galaxy Luminosity-Size Relation

Figure 2 shows the luminosity-size relation of the DGSS galaxies with photometric redshifts (*open circles*) superimposed over the contours of the selection function $S_{US}(M_{B_0}, R_d,\ z)$. This photometric redshift-based luminosity-size relation is nearly identical to the one measured from DGSS Keck redshifts (e. g. Figure 6, Simard et al. 1999). The observed luminosity-size relation shows an apparent systematic increase in mean disk surface brightness with redshift. Galaxies at $z \geq 0.5$ begin to exhibit systematically higher surface brightnesses than the Freeman value, and major deviations from the Freeman relation are seen above $z = 0.7$. As shown by the contours in Figure 2, this apparent increase is due to changes in the survey selection function as a function of redshift.

Table 1 gives the rest-frame surface brightness distribution parameters for both the Keck and photometric DGSS redshift samples. N_{gal} is the number of galaxies in a given redshift bin, $\overline{\mu}_{0_B}$ is the mean rest-frame B-band disk central surface brightness, and $\sigma(\mu_{0_B})$ is the surface brightness standard deviation. *Both the Keck and photometric redshift samples yield the same results.* When selection effects are ignored, there is a strong systematic increase in surface brightness comparable to what previous studies found. However, when the selection function is used to weigh galaxies in such a way that the selection function of the highest redshift bin is effectively applied to all redshift bins, there is *no* detectable increase in the surface brightness of high-redshift disks.

5. Conclusions

Photometric redshifts were shown to yield the same results as Keck redshifts for a survey of the galaxy luminosity-size relation out to $z = 1.1$. In addition to being inexpensive in observing time and effort, reliable photometric redshifts can be obtained for all galaxies in the imaging fields at magnitude limits fainter

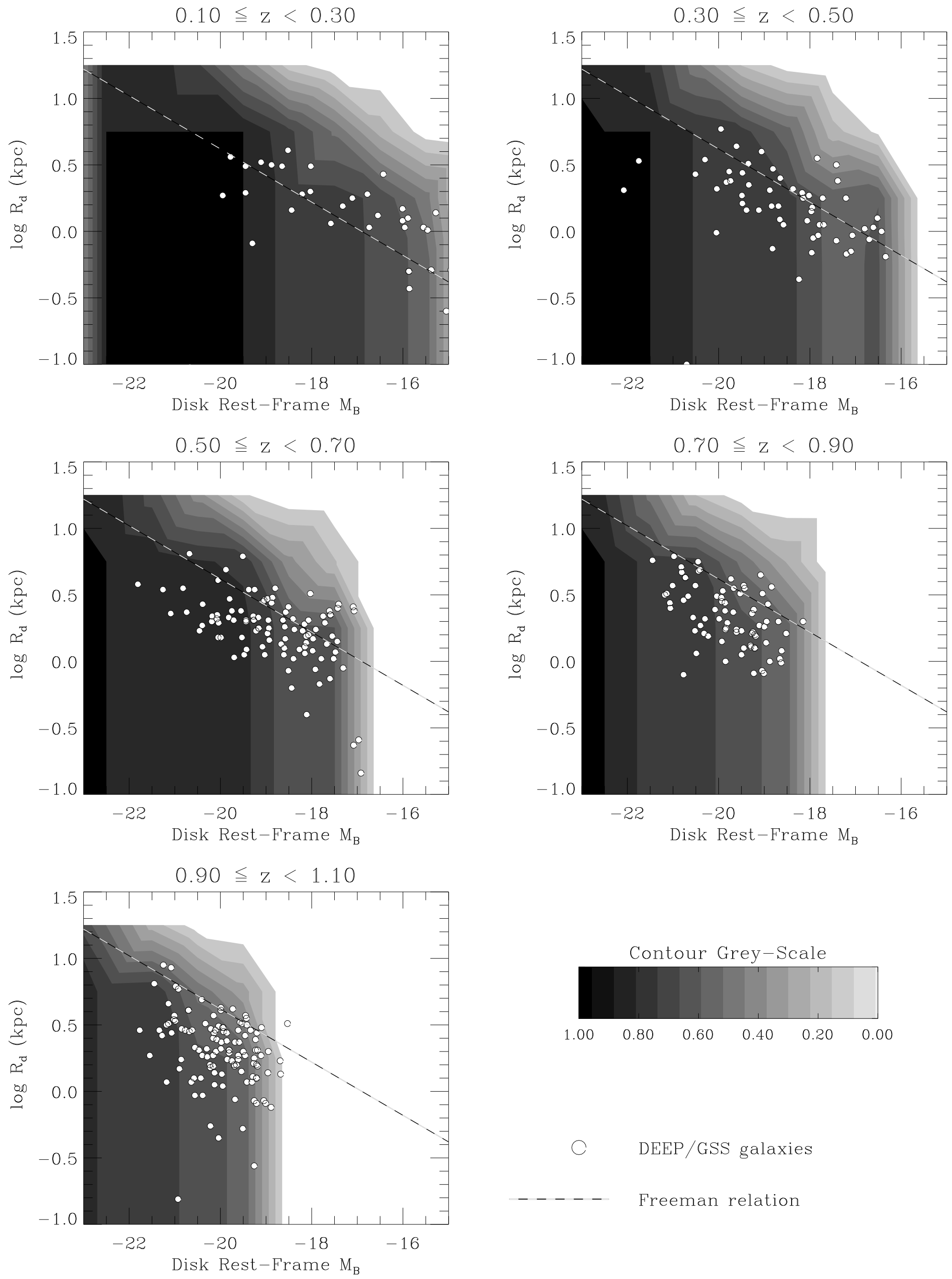

Figure 2. Rest-frame selection function $S_{US}(M_{B_0},\ R_d,\ z)$ (*shaded contours*) as a function of redshift. The highest contour was normalized to one in each redshift bin. $S_{US}(M_{B_0},\ R_d,\ z)$ was constructed using only photometric redshifts. Open circles are DGSS galaxies with photometric redshifts and $B/T < 0.5$, and the dashed line is the canonical Freeman relation for a disk central surface brightness $\mu_{0_B} = 21.65$ mag arcsec^{-2}. Note $H_0 = 70$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$ here.

Table 1. Rest-Frame Surface Brightness Distribution Parameters

DGSS Keck Redshift Sample

z	No Selection Function N_{gal}	$\overline{\mu}_{0_B}$	$\sigma(\mu_{0_B})$	With Selection Function N_{gal}	$\overline{\mu}_{0_B}$	$\sigma(\mu_{0_B})$
$0.10 \leq z < 0.30$	17	21.7 ± 0.3	1.2	5	20.3 ± 0.6	1.3
$0.30 \leq z < 0.50$	18	21.0 ± 0.3	1.2	6	20.2 ± 0.2	0.6
$0.50 \leq z < 0.70$	27	20.7 ± 0.2	0.8	14	20.3 ± 0.2	0.8
$0.70 \leq z < 0.90$	33	20.4 ± 0.2	1.1	31	20.2 ± 0.2	1.2
$0.90 \leq z < 1.10$	41	19.9 ± 0.2	1.4	41	19.9 ± 0.2	1.4

DGSS Photometric Redshift Sample

z	No Selection Function N_{gal}	$\overline{\mu}_{0_B}$	$\sigma(\mu_{0_B})$	With Selection Function N_{gal}	$\overline{\mu}_{0_B}$	$\sigma(\mu_{0_B})$
$0.10 \leq z < 0.30$	32	22.1 ± 0.2	1.2	4	20.6 ± 0.6	1.1
$0.30 \leq z < 0.50$	55	21.1 ± 0.2	1.2	19	20.4 ± 0.2	1.1
$0.50 \leq z < 0.70$	98	21.0 ± 0.1	1.1	36	20.4 ± 0.1	0.8
$0.70 \leq z < 0.90$	76	20.5 ± 0.1	0.9	64	20.3 ± 0.1	0.9
$0.90 \leq z < 1.10$	71	19.9 ± 0.2	1.3	71	19.9 ± 0.2	1.3

than possible with spectrographs. All these advantages combined with new large format CCD mosaics make photometric redshifts a powerful and economical way to increase current galaxy redshift samples by at least an order of magnitude.

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