RADIUS-DEPENDENT LUMINOSITY EVOLUTION OF BLUE GALAXIES IN GOODS-N

J. Melbourne, A. C. Phillips, J. Harker, G. Novak, D. C. Koo, and S. M. Faber
UCO/Lick Observatory, Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064; jmel@ucolick.org, phillips@ucolick.org, jharker@ucolick.org, novak@ucolick.org, koo@ucolick.org, faber@ucolick.org

Received 2006 March 1; accepted 2006 December 7

ABSTRACT

We examine the radius-luminosity (R-L) relation for blue galaxies in the Team Keck Redshift Survey (TKRS) of GOODS-N. We compare with a volume-limited, Sloan Digital Sky Survey sample and find that the R-L relation has evolved to lower surface brightness since $z = 1$. Based on the detection limits of GOODS, this cannot be explained by incompleteness in low surface brightness galaxies. Number density arguments rule out a pure radius evolution. It can be explained by a radius-dependent decline in $B$-band luminosity with time. Assuming a linear shift in $M_B$ with $z$, we use a maximum likelihood method to quantify the evolution. Under these assumptions, large ($R_{1/2} > 5$ kpc) and intermediate-sized ($3 < R_{1/2} < 5$ kpc) galaxies have experienced $\Delta M_B = 1.53^{+0.13}_{-0.10}$ and $1.65^{+0.08}_{-0.18}$ mag of dimming since $z = 1$. A simple exponential decline in star formation with an e-folding time of 3 Gyr can result in this amount of dimming. Meanwhile, small galaxies, or some subset thereof, have experienced more evolution, $2.55 \pm 0.38$ mag. This factor of 10 decline in luminosity can be explained by subsamples of starbursting dwarf systems that fade rapidly, coupled with a decline in burst strength or frequency. Samples of bursting, luminous, blue, compact galaxies at intermediate redshifts have been identified by various previous studies. If there has been some growth in galaxy size with time, these measurements are upper limits on luminosity fading.

Subject headings: catalogs — galaxies: evolution — galaxies: fundamental parameters — galaxies: starburst

Online material: machine-readable table

1. INTRODUCTION

Hierarchical clustering models (e.g., Baugh et al. 1998; Somerville et al. 2001) predict that galaxies assemble by the merger of smaller components with much of the size evolution of galaxies occurring since redshift $\approx 3$. Merger histories of galaxies can be traced by observables such as half-light radius, stellar luminosity, stellar mass, and metal abundance. In this paper we look for evidence of size-dependent, $B$-band luminosity evolution within blue galaxies to $z = 1$.

The study of distant galaxy sizes first became possible in the 1990s with the advent of high-resolution Hubble Space Telescope (HST) imaging. Lilly et al. (1998) used WFPC2 F814W images to investigate the radius-luminosity (R-L) relation for 341 galaxies in the Canada France Redshift Survey (CFRS). They found that large spiral galaxies undergo little size evolution between $z = 1$ and today. However, they found evidence for $\sim 1$ mag of surface brightness evolution (at fixed radius) for those same systems. They also indicated that smaller systems may be experiencing more evolution than large ones, but they did not quantify this statement. Simard et al. (1999) performed a similar study in a magnitude limited sample of 190 galaxies in the Groth Survey Strip ($i_{814} < 23.5$). While they found evidence for roughly 1.3 mag of surface brightness evolution ($z = 1$), they claimed that most of the apparent evolution could be produced by incompleteness effects. This conclusion was questioned by Bouwens & Silk (2002) in a paper presenting results from simulations of galaxy formation. They predicted 1.5 mag of evolution in the surface brightness of galaxies from $z = 1$ to today. They suggested that observed apparent evolution in the Simard et al. data set may be real and not the result of selection biases.

With the refurbishment of HST and the installation of the Advanced Camera for Surveys (ACS), such studies are now possible on a larger scale. Ravindranath et al. (2004), in an analysis similar to Simard et al. (1999), reported on the evolution of the R-L relation for disk galaxies in the Great Observatories Origins Deep Survey (Giavalisco et al. 2004) south field (GOODS-S). Using photometric redshifts, they reached fainter apparent magnitudes than previous studies. However, they limited their analysis to a small subsample of galaxies, which they believed to be 90% complete, based on the detection limits for smooth model galaxies. Constructing luminosity functions, they found no evidence for evolution in $L^*$ to $z = 1$.

Barden et al. (2005), who studied the R-L relationship for 5664 disk galaxies in the GEMS field, however, argued that both the Simard et al. and Ravindranath et al. results were biased by their strict surface brightness cuts. Specifically, both Ravindranath et al. and Simard et al. culled their data such that they were only studying the highest surface brightness tails of the galaxy luminosity distributions at all redshifts. Barden found that when they imposed the Ravindranath et al. strict surface brightness cut on their sample, it eliminated $\sim 70\%$ of the bright ($M_B < -20$) galaxies in the low-$z$ bin but only 10% of galaxies at high-$z$. Because they were only looking at the tails of distributions, there was no characteristic luminosity to compare to, resulting in a measurement of no surface brightness evolution. However, when Barden et al. instead applied their own selection function to all galaxies brighter than their high-$z$ magnitude limit of $M_B < -20$, they found that the central surface brightness has evolved significantly, 1.4 mag in the $B$ band out to $z = 1$. Barden et al. noted that their results mapped smoothly onto the R-L relation for nearby Sloan Digital Sky Survey (SDSS) galaxies, which was not true for the Ravindranath et al. and Simard et al. results. Interestingly, Barden et al. also showed evidence for an unchanging stellar mass-size relation for disk galaxies since $z = 1$. However, because galaxies are known to be star-forming, the stellar mass must be increasing, indicating that the size of galaxies must also be increasing to remain on the mass-size relation. They suggest that this is evidence for “inside-out” disk growth.

A study by Trujillo & Aguerri (2004) attempted to measure the size evolution of disk galaxies in the Hubble Deep Fields (HDFs; Williams et al. 1996). They compared the SDSS R-L relation from
Shen et al. (2003) with 218 galaxies in the HDF and specifically looked at how the mean and dispersion of galaxy sizes in a given luminosity bin changed with redshift. They found a modest increase in size with time, which could also be interpreted as a decrease in luminosity. Shen et al. (2003) with 218 galaxies in the HDF and specifically looked at how the mean and dispersion of galaxy sizes in a given luminosity bin changed with redshift. They found a modest increase in size with time, which could also be interpreted as a decrease in luminosity. Shen et al. (2003) with 218 galaxies in the HDF and specifically looked at how the mean and dispersion of galaxy sizes in a given luminosity bin changed with redshift. They found a modest increase in size with time, which could also be interpreted as a decrease in luminosity.

### Table 1

| TKRS-ID | R.A.
(J2000.0) | Decl.
(J2000.0) | z  | $m_g$ (AB) | $m_V$ | $m_i$ | $m_z$ | $M_B$ (Vega) | $(B-V)_{rest}$ | $r_i$ (arcsec) | $R_B$ (kpc) |
|---------|-----------|-----------|----|-----------|------|------|------|-------------|----------------|---------------|-------------|
| 117     | 12 36 55.897 | 62 21 38.17 | 0.585 | ... | 23.781 | 23.213 | 23.040 | -18.642 | 0.397 | 0.668 | 4.467 |
| 239     | 12 36 20.286 | 62 17 29.60 | 0.848 | ... | 23.724 | 22.678 | 22.120 | -20.421 | 0.648 | 0.381 | 2.848 |
| 320     | 12 36 32.725 | 62 18 44.77 | 0.483 | ... | 24.274 | 23.656 | 23.845 | -17.660 | 0.411 | 0.220 | 1.074 |
| 345     | 12 35 43.068 | 62 12 55.89 | 0.851 | 24.552 | 23.663 | 22.859 | 22.008 | -20.402 | 0.733 | 0.540 | 4.238 |
| 428     | 12 37 05.851 | 62 22 30.74 | 0.487 | 24.357 | 23.792 | 23.201 | 23.696 | -18.154 | 0.412 | 0.536 | 2.804 |
| 432     | 12 36 31.162 | 62 19 05.01 | 0.681 | 23.716 | 22.693 | 21.759 | 21.450 | -20.507 | 0.561 | 0.632 | 4.551 |
| 444     | 12 36 01.540 | 62 15 13.41 | 0.298 | ... | 22.085 | 21.487 | 21.183 | -18.416 | 0.581 | 0.918 | 3.863 |
| 445     | 12 36 51.450 | 62 20 53.33 | 0.744 | 22.886 | 22.198 | 21.729 | 20.591 | 0.407 | 0.943 | 6.739 |
| 448     | 12 36 53.680 | 62 21 11.31 | 0.472 | 23.057 | 22.181 | 21.683 | 21.466 | -19.640 | 0.419 | 0.869 | 5.167 |
| 463     | 12 36 34.427 | 62 18 46.99 | 0.503 | 24.858 | 24.082 | 23.449 | 23.352 | -17.976 | 0.446 | 0.321 | 1.778 |
| 484     | 12 36 41.056 | 62 19 35.23 | 0.609 | 24.485 | 24.256 | 23.961 | 24.351 | -17.877 | 0.221 | 1.106 | 7.475 |
| 555     | 12 36 08.002 | 62 15 53.71 | 0.459 | ... | 21.821 | 21.244 | 21.025 | -19.948 | 0.442 | 1.023 | 7.029 |
| 584     | 12 35 59.725 | 62 14 46.63 | 0.531 | 23.765 | 22.807 | 22.108 | 21.859 | -19.444 | 0.513 | 0.580 | 3.923 |

**Notes:** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

*Wirth et al. 2004.*

The GOODS team obtained very deep imaging data in two 10′ × 16′ fields using the HST Advanced Camera for Surveys. This effort included four separate passbands: F435W, F696W, F775W, and F850LP (B, V, i, and z), which allow for good matching to spectral energy distributions and determination of K-corrections. Our study uses the mosaic data (0.035′ pixels) from the northern field (GOODS-N), which is centered on the Hubble Deep Field—North but covers a much larger area.

We limit our study to those GOODS galaxies targeted by TKRS (Wirth et al. 2004), which obtained spectra of 2018 objects in the GOODS-N field. This magnitude-limited survey targeted objects with $R_{AB} ≤ 24.4$, identified on deep ground-based images. TKRS
made no effort to exclude objects that appeared starlike, so the survey is not biased against compact galaxies. The survey obtained reliable redshifts for 1440 galaxies and spectroscopically identified 96 Galactic stars.

2.2. Photometry

2.3. Elliptical Aperture Photometry

We measured photometric properties of the TKRS sample with the STSDAS program ellipt, which provides flux and intensity measurements within elliptical apertures of increasing semimajor axis; ellipt performed between 1000 and 2000 iterations to fit the central coordinates, ellipticity, and position angle at every semimajor axis radius. Radii were incremented with a geometrical step of 0.0015 from a minimum radius of 0.003 to a maximum of 6, well out to the sky for all but the largest low-z elliptical galaxies in our sample. The centers and ellipticities were allowed to vary at each radius. We did the initial fitting with the i-band image, the deepest of the four bands. The i-band ellipses were then applied for photometry in the other three bands.

While running ellipt, neighbor galaxies were masked out with SExtractor (Bertin & Arnouts 1996) segmentation images. We set the SExtractor detection parameters to maximize the mask-allowing of neighbors, while retaining the structure within a given galaxy. Specifically, we set the detection and analysis thresholds to 2.5 σ, and the deblend_mincont to 0.10. The detection_minarea was set to 25 pixels. Final segmentation maps were created by adding together the maps from the i- and i-band images. We found that while the i-band map did a better job of detecting the wings of galaxies, the i-band image was important for identifying regions of young stars. After combining the segmentation maps from the two filters, we smoothed them with a boxcar of 10 pixels. This, for instance, filled in the pixels between spiral arms that might not have been included in the original maps and extended the segmentation images into the lower surface brightness wings of the galaxy. Final maps were inspected by eye and any pixels that were masked but belonged to the actual galaxy being measured were corrected.

2.4. Magnitudes and Half-Light Radii

Total magnitudes, half-light radii, concentration parameters, and surface brightnesses were calculated from the ellipt measurements using a curve-of-growth technique. For each image, we employed an iterative process. An initial sky level was chosen as the flux level at which the intensity of light in successive annuli remained constant. After subtracting the sky value, a total galaxy flux was determined as the flux level at which the enclosed flux remained constant in successive apertures. If the enclosed flux was found to fall off with large radius, the sky level was reduced and a new total flux calculated. If the enclosed flux was found to increase with radius without bound, the sky level was increased and the process begun again.

Neighbors were often near enough to contaminate the sky background measurement. SExtractor segmentation images were used to identify and mask out these contaminants. Cases where the masking failed to subtract the entire influence of a neighbor were identified by inspection and corrected individually.

We converted apparent magnitudes to absolute $M_B$ (Vega) and rest-frame colors, $U - B$ and $B - V$ (Vega), using the K-correction routine described in Willmer et al. (2006).

Apparent half-light radii ($r_{50}$) were given by the semimajor axis that enclosed half the flux. We corrected apparent radii for the point-spread function (PSF) of the image by subtracting the radii of stellar sources in quadrature (Phillips et al. 1997). To avoid possible variations of radius with passband, we measured size in all four filters and then estimated the rest-frame $B$-band half-light radius from a weighted mean of the results. Weigh weights were assigned by the overlap of the filter passband with the rest-frame $B$ filter. Using the angular-diameter distance, we calculated rest-frame $B$-band half-light radii in kpc ($R_{1/2}$). A concentration measurement was made from the i-band images, $C_{80:20} = \log(r_{80}/r_{20})$, where $r_{80}$ is the radius that contains 80% of the galaxy light.

Table 1 summarizes the results of the elliptical photometry of the TKRS sample of galaxies. Column (1) is the TKRS ID number (Wirth et al. 2004); columns (2) and (3) contain the right ascension and declination, respectively; column (4) gives the redshift (Wirth et al. 2004); and columns (5)–(8) give the elliptical-measured magnitudes in the four GOODS bands. Columns (9) and (10) are $M_B$ and $B - V$ rest, respectively; column (11) contains the i-band apparent half-light radius, $r_{50}$ (in arcseconds); and column (12) gives the rest-frame $B$-band half-light radius, $R_{1/2}$ (in kpc).

2.5. Selecting Blue Galaxies

Recent studies (Blanton et al. 2003b; Bell et al. 2004; Weiner et al. 2005) demonstrate that galaxy populations are bimodal in optical color. The color-magnitude diagram for TKRS also shows that galaxies fall into two regions in color space, blue galaxies and red-sequence galaxies, with a trough separating the two groups. The color of this trough is roughly $(B - V)_\text{rest} = 0.7$ (Vega) for the TKRS sample. Locally, the trough is redder by about 0.1 mag. Red galaxies tend to be ellipticals and early-type, bulge-dominated spirals, both with high central surface brightness. The TKRS red sequence galaxies, for instance, tend to have high concentrations, $C_{80:20} \sim 0.9$, compared with the typical blue galaxy, $C_{80:20} \sim 0.6$. Therefore, the red galaxies tend to follow a separate $R-L$ relation from blue galaxies. As this would complicate our analysis, we choose to leave the red galaxies out of our sample. Except where noted, the rest of this paper discusses the TKRS galaxies bluer than the trough $[(B - V)_{\text{rest}} < 0.7]$, which tend to be later-type spirals, irregulars, and compact blue galaxies. We also eliminate 10 obvious AGN (active galactic nucleus) galaxies based on their images and spectra.

2.6. Photometric Accuracy

We tested for the photometric accuracy of our measurement methods in two ways. First we created idealized exponential disk model galaxies with known sizes and luminosities and measured them in the same way as the GOODS galaxies. However, because real blue galaxies often contain structure from star-forming regions, spiral arms, or bars, our “smooth” model galaxies may not be adequate for understanding our measurement errors. As a result, we also performed an additional test using real galaxies in the Ultra Deep Field (UDF; GO 9978; principal investigator S. Beckwith). In this second test we compared measurements of galaxies observed in the UDF (2 mag deeper than GOODS) with measurements of the same galaxies observed to the GOODS depth. If our techniques are mismeasuring the low surface brightness components of galaxies, there should be an offset in the sizes and luminosities of galaxies measured at the two significantly different depths. While the measured radii of our large low-surface brightness model galaxies tend be underestimated, the radii of actual galaxies do not seem to have this bias. The details of these studies are discussed in the following two subsections.

2.6.1. Photometry of Model Galaxies

To check the accuracy of our photometry, we measured over 3000 model disk galaxies, spanning the range of apparent magnitudes
The results of the model photometry indicate that for most isolated sources, our methods produce accurate measurements (luminosity to better than 0.1 mag and radii to better than 10% for $m_{in} < 23$). As the input radii and magnitudes increase, the scatter rises significantly. However, by taking groups of galaxies in aggregate, we can expect a representative picture of the galaxy population above our magnitude cutoff out to $z = 1$. While these model galaxies were made with a Gaussian PSF, we checked to make sure that our measurements would not change significantly for ACS PSFs, which can have significant wings. We created 10 additional models spanning our range of size and luminosity and convolved with the ACS $z$-band PSF from Tiny Tim (Krist 1995). We measured them in the same way as the original models and found no significant difference in the photometry.

2.6.2. Photometry in the UDF

In the previous section we tested our photometric methods on smooth model galaxies of known size and luminosity. While this test would have revealed any significant measurement errors for bright systems, it may not tell us much about measuring actual galaxies especially at fainter luminosities. Actual galaxies can have disturbed morphologies and light profiles that are not well fit by smooth profiles. We looked for additional measurement biases in our photometry by measuring galaxies in the UDF. Galaxies with an apparent luminosity $i < 25$, were identified in the UDF with the SExtractor search algorithm. We measured the apparent size and luminosity of these galaxies in both the UDF and the GOODS depth image of the UDF. Because the UDF is 2 mag deeper than the GOODS equivalent image, low surface brightness features will be easier to measure in the UDF.

Figure 2 shows a comparison of photometry from the UDF with the GOODS equivalent of the UDF. For bright systems, $i < 23$, measurements of magnitude and size are equivalent to within 10%. For fainter systems the scatter increases, but is not biased. This is another indication that low surface brightness wings of galaxies are not being missed by the GOODS images, and our photometry is accurate even to faint levels.

2.7. Local SDSS Data

In § 3 we will use a complete, volume-limited SDSS galaxy sample as a local reference for evolution in the $R$-$L$ plane. The steps to generate the local SDSS $R$-$L$ relation are described below.

We select a statistically complete sample of blue galaxies from the SDSS DR2 catalog with redshifts $0.01 < z < 0.1$ and apparent Petrosian magnitudes, $14 <= r_p <= 18.0$. Half-light radii and luminosities were measured by L. Simard et al. (2007, in preparation) with the GIM2D (Simard 1998) Sersic model fitting routine. The semimajor axis, half-light radii were corrected for PSF effects. Magnitudes were converted from Sloan $g$ and $r$ to $B$ and $V$ using equation (23) of Fukugita et al. (1996).

From this set we drew a volume-limited sample that accounted for both the low and high apparent magnitude selection criteria. To do this, we selected galaxies of a given absolute magnitude in the redshift slice for which they are complete. For instance, we drew high-luminosity galaxies from the high-$z$ end of our SDSS sample (i.e., $z \sim 0.1$) and drew low-luminosity galaxies from the low-$z$ end. We scaled the numbers of galaxies in each narrow $z$-bin to a common volume. In order to confirm that our volume-limited SDSS number distributions are valid, we generated a luminosity function (using both red and blue galaxies) and compared with Blanton et al. (2003a). We convert our $B$-band luminosities to SDSS $g$-band by assuming a typical galaxy color for blue galaxies of $g - B = -0.35$ (Fukugita et al. 1995, Table 3). Figure 3...
shows the Blanton et al. result (solid line) and ours (dashed line). The two luminosity functions are well matched except at the brightest end, where the large statistical variations are due to small numbers of sources. This test confirms that our volume-limited SDSS sample is indeed representative of the local universe.

3. SELECTION FUNCTION

3.1. Detectability of Low Surface Brightness Galaxies

We attempted to quantify the incompleteness effects that might bias the detection of galaxies in $R$-$L$ space. Low surface brightness galaxies at high redshift are the hardest for SExtractor algorithms to detect and the hardest for spectroscopic redshift determinations. As detailed below, we studied selection biases introduced by low surface brightness galaxies in three ways and found that our sample was not missing large numbers of these galaxies.

First we investigated the detectability of the largest observed disk galaxies in the TKRS sample with redshifts near $z = 1$. Figure 4 shows the five largest galaxies in the sample near $z \sim 1$. These objects are not the relatively smooth disks that one finds locally. In part because of the “morphological K-correction,” they contain significant, high surface brightness substructure, which makes them much easier to detect than smooth disks. In order to check whether substructure can assist search algorithms, we extracted these galaxy images, doubled their diameter while conserving their flux, and placed them back into the GOODS images at random locations. All of these galaxies were still detected both visually and by SExtractor search algorithms. Furthermore, the multiple, compact, blue regions seen in these objects make them candidates for strong nebular emission lines, which allow for easy redshift determination. If the five galaxies in Figure 4 are representative of large blue galaxies at $z = 1$, then large galaxies are not being systematically missed in the GOODS catalogs. In this case, several of the previous studies including Ravindranath et al. (2004) may have overestimated their selection effects at high-$z$ because they selected galaxy samples with cuts based on the detection of smooth, model galaxies rather than the knotty galaxies that actually exist at high redshift.

Second, we searched for low surface brightness galaxies in the GOODS fields that were not part of TKRS. We rebinned and
smoothed the GOODS images and looked for objects that were not obvious in the original frames. When we performed this experiment over 1/4 of the field with different smoothing lengths (up to 1/3), we found one additional large galaxy. This galaxy was actually detected by the GOODS SExtractor catalog, but as several objects rather than as a single galaxy. Inspection by eye revealed that this object is most likely a single galaxy with multiple faint knots of star formation.

In a final check for low surface brightness galaxies, we ran the SExtractor search algorithm on both the UDF and the shallower GOODS images, first running ellipse measurements in the same way as the TKRS sample, then comparing the distributions and look for evolutionary trends, under the assumption that incompleteness effects are negligible. For instance, if there were no evolution in the R-L relation, we would expect that the number and distribution of objects in boxes 1 and 2 to remain constant. However, over time (from $z = 1$ to the present), boxes 1 and 2 contain successively fewer galaxies, suggesting evolution. This is not the result of selection biases, which would tend to produce the opposite effect. The evolution may be occurring in one or more of the following parameters: luminosity, radius, or number density. If we attribute the entirety of the evolution to a change in luminosity, galaxies are moving to lower luminosities (a blue shift to the left) over time, emptying the boxes. Note that under the assumption that sizes are not changing, this is equivalent to the surface brightness evolution discussed in the literature.

In the case of pure radius evolution, galaxies would be growing hierarchically in size (a shift up in Fig. 6) over time, emptying box 2 before box 1. A model of pure radius evolution is somewhat unphysical in that the growth of galaxy stellar mass at large radii would presumably also increase luminosity. In order for galaxies to change only in size and not in magnitude, the increase in luminosity from new star formation would have to be

objects in GOODS-N with those in the TKRS catalog. We have already demonstrated that the GOODS SExtractor catalogs have no significant bias against low surface brightness galaxies down to the magnitude limit of TKRS. Thus all that remains to check is what biases exist in the spectroscopic sample. To do this we measured apparent size and luminosity for the $i < 25$ galaxies in the GOODS-N SExtractor catalog. The GOODS-N galaxies were measured in the same way as the TKRS sample, first running ellipse and then our curve-of-growth code of postage stamp images of each galaxy.

The left panel of Figure 5 plots $r_{50}$ versus $m_i$ for the GOODS-N galaxies. Galaxies with successful TKRS redshift measurements are shown in green. Those targeted but without a $z$ measurement are shown in red. The plot is binned in both the radius and magnitude directions. In the right panel of Figure 5 the ratio of successful $z$'s to GOODS galaxies in a bin is the top number in that bin. The ratio of successful to targeted is the middle number, and the total number of GOODS galaxies in each bin is the bottom number.

The plot shows that the major incompleteness occurs near the magnitude limit. At a fixed magnitude, there is almost no drop off in success rate with radius, and thus with surface brightness. Assuming that all of the galaxies in a bin are within the redshift range of TKRS, the top number in the bin summarizes the total TKRS selection function for galaxies of that size and brightness. When measuring evolution in the R-L plane, we use the top number to correct for selection biases in our sample. Because some of the galaxies without $z$'s may be at higher redshift than $z = 1$, we may be over estimating the incompleteness correction.

4. RADIUS-LUMINOSITY RELATION

Figure 6 shows the rest-frame radius-luminosity relation for blue galaxies in TKRS to $z = 1.2$. The redshift range of each bin has been selected to maintain equal volume, $\sim 3 \times 10^4$ Mpc$^3$. The color of each galaxy is indicated and red boxes, labeled 1 and 2, are repeated in every panel to help guide discussion. The general trend, best seen in the lowest redshift bin, is that large galaxies tend to be bright and small galaxies tend to be faint. In successive redshift bins, the sample has a low-luminosity cutoff set by the TKRS apparent magnitude limit.

Because the bins are equal volume, it is possible to visually compare the distributions and look for evolutionary trends, under the assumption that incompleteness effects are negligible. For instance, if there were no evolution in the R-L relation, we would expect that the number and distribution of objects in boxes 1 and 2 to remain constant. However, over time (from $z = 1$ to the present), boxes 1 and 2 contain successively fewer galaxies, suggesting evolution. This is not the result of selection biases, which would tend to produce the opposite effect. The evolution may be occurring in one or more of the following parameters: luminosity, radius, or number density. If we attribute the entirety of the evolution to a change in luminosity, galaxies are moving to lower luminosities (a shift to the left) over time, emptying the boxes. Note that under the assumption that sizes are not changing, this is equivalent to the surface brightness evolution discussed in the literature.

In the case of pure radius evolution, galaxies would be growing hierarchically in size (a shift up in Fig. 6) over time, emptying box 2 before box 1. A model of pure radius evolution is somewhat unphysical in that the growth of galaxy stellar mass at large radii would presumably also increase luminosity. In order for galaxies to change only in size and not in magnitude, the increase in luminosity from new star formation would have to be

3.2. The TKRS Selection Function

Redshift surveys are almost always biased against faint objects due to the increased difficulty of identifying spectroscopic features. To quantify selection biases in the TKRS catalog, we compared the distribution of apparent radii and magnitudes for
balanced by a simultaneous fading of the other stars in the galaxy. While contrived, it will be interesting to investigate if the data can rule out a pure radius evolution scenario.

The third case, number-density evolution would reduce the numbers of galaxies in boxes 1 and 2 if the overall number of blue galaxies were declining with time. Number density evolution can occur through mergers of systems or by migration of blue galaxies to the red sequence. It is interesting that the luminous end of the radius-luminosity relation shown in Figure 6 tends to be populated by redder galaxies at all redshifts. Results from recent work on the evolution of the luminosity function for luminous blue galaxies (Faber et al. 2005) indicate that such a number density evolution, if happening, is small. Therefore, we will assume constant number density for this paper.

More complex evolutionary scenarios are possible. For instance, the shape of the $R-L$ distribution at a given size may change. This would be the result if a subset of galaxies of a given size experienced a luminosity enhancement at high redshift, while the bulk of galaxies of that size remain in a “normal” state. However, our relatively small sample precludes exploration of these more complicated scenarios.

The rest of this section will be dedicated to quantifying the evolution indicated in Figure 6 out to $z = 1$. The figure indicates that the evolutionary trends continue beyond $z = 1$; however, because of small number statistics, we choose to limit ourselves to galaxies below this redshift limit. We use the previously defined SDSS sample of low-$z$ galaxies for a local reference.

4.1. Luminosity Evolution

First we investigate the case of luminosity evolution. Figure 7 replots the TKRS $R-L$ distributions (black), as histograms of galaxy magnitude, binned by size, and equal volume redshift bins to $z = 1$. The local SDSS distributions (red) are separated into the same size and magnitude ranges. The amplitude of the SDSS distributions are scaled to match the same volume as the TKRS distributions ($\sim 3 \times 10^8$ Mpc$^3$) and are plotted in each $z$-bin.

| KTRS ID | $z$  | $r_{50}$ kpc | $M_b$ | $B-V$ | $B$  | $V$  | $i$  | $Z$  |
|---------|------|--------------|-------|-------|------|------|------|------|
| 12771   | 0.938| 11.106       | -21.87| 0.529 |      |      |      |      |
| 3325    | 0.944| 11.520       | -20.44| 0.593 |      |      |      |      |
| 9631    | 1.022| 12.045       | -21.66| 0.553 |      |      |      |      |
| 3752    | 1.447| 13.484       | -22.53| 0.517 |      |      |      |      |
| 5883    | 1.148| 16.628       | -20.06| 0.490 |      |      |      |      |
as a reference. These plots indicate that, in the lowest-$z$ bin, the SDSS distributions are similar to TKRS with some modest luminosity evolution. As redshift increases, the peaks of the TKRS distributions shift toward higher luminosities.

Several effects should be noted while examining these distributions. The sharp cutoff on the faint end of the GOODS distributions (especially at higher $z$) is the result of the apparent magnitude limit of the TKRS survey. The SDSS data, however, are complete to $M_B = -16$, meaning that the observed turnover of the SDSS distributions at fainter magnitudes for large and medium-sized galaxies is real. Although this turnover is not revealed for the small systems, the steep decline in numbers of objects at the bright end is an alternative marker for tracking evolution.

Assuming that the SDSS sample represents the local universe, what is the likelihood that the TKRS sample was drawn from the local distribution? Figure 7 indicates that the two samples differ significantly. We develop models for luminosity evolution and apply them to the SDSS curves. We test which models produce the best match between the two distributions.

We have chosen a simple model where magnitude evolves linearly with redshift, such that

$$\Delta M_B(z) = \alpha z.$$  \hfill (1)

This model assumes that the shapes of the magnitude distributions do not change with redshift; it is a pure shift in luminosity for galaxies of a given size. We use a maximum likelihood method to recover the most likely $\alpha$ for galaxies in each size bin. We begin by assuming a value for $\alpha$. For each TKRS galaxy in a given size bin, we shift the SDSS number distribution by $\Delta M_B(z)$ to the TKRS galaxy redshift. We then cut the SDSS number distribution at the TKRS magnitude limit for that redshift, and normalize it to unity creating a probability distribution. We calculate the likelihood of this TKRS galaxy being in our shifted SDSS sample. Likelihood is given by the probability associated with a galaxy of given $M_B$ and $R_{1/2}$ read from the shifted and normalized SDSS probability distribution, multiplied by the galaxy’s TKRS selection bias (top number from Fig. 5). Finally, we sum ln (likelihood)
In general, galaxies of a given radius in this ensemble appear to have faded before box 1. Mergers would presumably move galaxies up and to the right over (but not in luminosity) they would tend to shift up in this plot, emptying box 2 to the left in this plot, emptying boxes 1 and 2. If galaxies are growing in size provided for reference. If galaxies are fading with time they would tend to shift between 0.4 and 0.55. Blue points have color bluer than 0.4. The red boxes are for all galaxies at all redshifts in a given size bin. We repeat this for large, intermediate and small galaxies is then 1\,\kpc. Larger sample sizes may help to identify the causes for these differences. Some of the measured evolution may be the result of changing AGN populations within the TKRS sample. If we remove all Chandra sources (Chandra Deep Field–North; Alexander et al. 2003) from TKRS (89 galaxies within 1.5\,\kpc of a Chandra source), there is a modest change in the results. The measured evolutions for large, intermediate and small galaxies is then 1.33 ± 0.13, 1.48 ± 0.10, and 2.23 ± 0.18, respectively. This indicates that most of the evolution is not the result of a change in the number density of AGNs.

4.2. Radius Evolution

We now perform a similar analysis to look for evolution in the half-light radius, dividing the sample into three luminosity bins (Fig. 11). Once again the TKRS data are shown in black and the SDSS data are shown in red. Because the redshift bins are equal volume, we can readily see that this plot is not consistent with pure radius evolution. If pure radius evolution were occurring, the total number of galaxies within a given luminosity bin would be constant over time, while the peaks of the distributions would shift to larger radii. Instead, the total numbers of objects within each magnitude bin are declining over time, with the largest decline in the brightest magnitude bin. In fact, in the most luminous bin, SDSS predicts no galaxies within the given volume at the present day. In contrast, TKRS shows that there are 24 galaxies in this same luminosity bin by z = 1. Note, the highest redshift, lowest luminosity bin in Figure 11 is compromised by the magnitude limit of TKRS.

Figure 11 is consistent with significant luminosity evolution. The drop in number of luminous objects with time is a prediction of luminosity evolution. The fact that the SDSS and TKRS samples do not match well in the low-z bin is also explainable by the significant luminosity evolution predicted in the previous section. Recall that by z = 0.5 we are predicting more than half a magnitude of luminosity evolution. Figure 12 reproduces Figure 11, now applying our measured radius-dependent luminosity evolution and TKRS selection function to the SDSS sample. Again, pure luminosity evolution is shown to be a good explanation for

![Figure 6](image_url) - Half-light radius of blue TKRS galaxies plotted against absolute magnitude in equal volume bins between z = 0 and 1.2. Red points have (B − V)_{AB} color between 0.55 and 0.7. Yellow points have (B − V)_{AB} color between 0.4 and 0.55. Blue points have color bluer than 0.4. The red boxes are provided for reference. If galaxies are fading with time they would tend to shift to the left in this plot, emptying boxes 1 and 2. If galaxies are growing in size (but not in luminosity) they would tend to shift up in this plot, emptying box 2 before box 1. Mergers would presumably move galaxies up and to the right over time. In general, galaxies of a given radius in this ensemble appear to have faded since z = 1.25 and galaxies in boxes 1 and 2 appear to have gotten redder.

For all galaxies at all redshifts in a given size bin. We repeat this process with a range of values for α to find the most likely magnitude shift between the SDSS and TKRS distributions.

Figure 8 plots ln (likelihood) versus α and reveals the luminosity evolution experienced by galaxies of each size bin to z = 1. In order to decrease noise, the likelihood curves are boxcar smoothed with smoothing length of 0.1 mag. The most likely evolution is given by the peak of each curve (solid line), while the representative errors (dashed lines) are given by the locations where ln (likelihood) drops by 0.5 (for a description of the maximum likelihood method, see Kendall et al. 1987). Interestingly, galaxies of different sizes seem to be experiencing different amounts of luminosity evolution. While the analysis indicates that large and intermediate-sized galaxies have experienced roughly equivalent evolutions of 1.53^{+0.13}_{-0.10} and 1.65^{+0.08}_{-0.18} mag, respectively, small galaxies appear to have experienced significantly more, 2.55 ± 0.38 mag. The result for galaxies with small size is different from the results for larger galaxies at about the 2 σ level, suggestive of a radius-dependent luminosity evolution. If we do not smooth the likelihood curves or we fit for the peak, the results are virtually identical and well within the errors.

We check whether the change in α with radius is abrupt by repeating the maximum likelihood technique on smaller size bins. The results, shown in Figure 9, indicate that a transition may be occurring for objects with sizes smaller ~2 kpc. Larger sample sizes, especially for small galaxies will help to confirm or disprove the claim of size dependence on the luminosity evolution. This may be possible in on-going and future redshift surveys such as the Deep Extragalactic Evolutionary Probe 2 (DEEP2).

Figure 10 shows the same TKRS distributions (black) as in Figure 7, but now the SDSS distributions (red) are shown with the simple luminosity evolution model and the TKRS selection function applied. Thus the red curves now represent the distribution our model predicts for TKRS, given the evolved SDSS distribution. Aside from small differences in the total number of objects, the red and black curves match well. The differences in number density could reflect an actual evolution in number density that we are not accounting for in our models. It could also result from overestimating the selection bias. For example, if a large sample of the galaxies in Figure 5 are at higher redshift than the galaxies targeted by TKRS, then we would be overestimating the selection bias. Other factors might contribute to the differences in the two samples, for instance cosmic variance, or some more complex evolutionary scenario. Deeper studies with larger sample sizes may help to identify the causes for these differences.

The results, shown in Figure 12, indicate that a transition may be repeating the maximum likelihood technique on smaller size bins. If we do not smooth the likelihood curves or we fit for the peak, the results are suggestive of a radius-dependent luminosity evolution. If we do not smooth the likelihood curves or we fit for the peak, the results are virtually identical and well within the errors.
the differences between the SDSS and TKRS samples. Note that two intermediate-luminosity bins (0.79 < z < 1.0) show fewer SDSS galaxies than expected. This may be another indication for more complicated evolutionary scenarios.

5. DISCUSSION

We have demonstrated evolution in the radius-luminosity relationship for blue galaxies. Based on number density constraints, this evolution cannot be explained as a pure radius evolution. It can, however, be explained by a radius-dependent luminosity evolution. We have modeled this evolution as a simple shift in luminosity that increases linearly with redshift. In this section we describe how our results compare to previous work and attempt to provide a physical mechanism that might give rise to the measured luminosity evolution. We first examine the results from large and intermediate-sized galaxies, which appear to be experiencing similar evolution, roughly a factor of 4 decrease in luminosity since z = 1. We then discuss the more surprising result from
galaxies with small size that appear to have evolved by nearly a factor of 10 in luminosity.

5.1. Evolution of Large and Intermediate-sized Galaxies

A consistent picture is beginning to emerge for the evolution of large and intermediate-sized blue galaxies. Our results for large and intermediate-sized galaxies are well matched to the findings in Barden et al. (2005), who examined the R-L relation in the GEMS field. They found a central B-band surface brightness evolution of ~1.4 mag for disk galaxies. Our measured evolution is consistent although slightly larger, perhaps due to different selection criteria. We selected all blue galaxies, while Barden et al. selected galaxies with an exponential Sersic profile, so we may be including more centrally concentrated objects such as AGNs. Our sample includes 89 X-ray sources, which may be harboring central AGNs. If we remove these sources from our sample we measure a somewhat smaller evolution (~0.2 mag for each size bin), in better agreement with Barden et al. It should be noted, however, that the differences between our results and Barden et al. are small compared with the uncertainties.

Our results are also well matched to Trujillo & Aguerri (2004), who looked for surface brightness evolution disk galaxies within the HDF. Assuming that the surface brightness evolution is driven by luminosity evolution they find a V-band luminosity evolution of roughly 0.8 mag by z = 0.7. Assuming some small color evolution of 0.1–0.2 mag, suggested by Figure 6, this is, to within errors, what we predict for large and intermediate-sized galaxies (~1.1 ± 0.2 mag by z = 0.7). Trujillo & Aguerri (2004) also investigated a size-only evolution model. They used the SDSS galaxy sample of Shen et al. (2003) as a local baseline for the R-L relationship, but they did not consider the number density of galaxies in given size and luminosity bins. Specifically, because Shen et al. encompasses a much larger volume than the HDF, the samples especially for bright systems are not comparable. As we show when volumes are considered, the radius-only evolution interpretation does not work.

In addition to luminosity evolution, Barden et al. (2005) also showed evidence for constant stellar mass surface density in disk galaxies since z = 1. They interpreted this as evidence for inside out disk growth. If we adopt a 25% growth in half-light radius for our galaxies since z = 1 and apply it to our SDSS reference sample, we can reemasure the expected amount of additional luminosity evolution in the sample. As a simple model, we assume that the size evolution is linear with redshift and that all galaxies are growing at the same rate. The resulting luminosity evolutions since z = 1 are then 1.18±0.13, 1.33 ± 0.10, and 1.75±0.45 for large, intermediate, and small galaxies, respectively. Under this scenario, a significant amount of the surface brightness evolution is from the increasing galaxy size, and therefore the measured

![Fig. 8.—Plot of ln (likelihood) vs. $\alpha = \Delta M_B(z = 1)$ for the three galaxy size bins. In order to minimize the effects of noise, the likelihood curves are boxcar smoothed with smoothing length of 0.1 mag. The peak of each curve (solid vertical line) represents the most likely evolution, while the errors are given by a ln (likelihood) drop of 0.5 (dotted lines). Given the input model, large and intermediate-sized galaxies have evolved by 1.53±0.13 and 1.65±0.08 mag, respectively. Small galaxies appear to have evolved by an additional magnitude, with $\Delta M_B(z = 1) = 2.55 \pm 0.38$ mag, different from the results for larger galaxies at about the 2 $\sigma$ level. If we do not smooth the likelihood curves or we fit for the peak, the results are virtually identical and well within the errors.](image)

![Fig. 9.—Plot of the dependence of $\alpha$ on galaxy size. We repeat the maximum likelihood method with smaller radius bins (black points) with width 0.18 in log ($R_{1/2}$). The results for the larger, original radius bins are repeated in red. A $\chi^2$ test of the black points rules out, at the 2 $\sigma$ level, an evolutionary model with constant luminosity evolution for galaxies of all radii. This suggests that the upturn in $\alpha$ at small radii is real. Larger samples, especially of small galaxies, will help to test these results.](image)
luminosity evolution is smaller. Thus, if galaxies really have grown in size with time, our measurements of luminosity evolution from the previous section are upper limits.

Trujillo & Pohlen (2005) looked for evidence of size evolution in disk galaxies. They measured luminosity and truncation radii in 21 of 36 disk galaxies in the UDF. They next applied the 1.4 mag luminosity evolution suggested by Barden et al. to their high-\(z\) \(R-L\) relation. They found it was still offset from their own measured local \(R-L\) relation (their Fig. 2). The offset in the two samples was largely the result of the four smallest galaxies in their high-\(z\) sample. The offset could be from truncation radius growth, or it could be from additional luminosity fading. They claim that an additional 25% growth in truncation radius can account for the offset. If, however, these smaller galaxies were evolved by our measured luminosity evolution (2.55 mag since \(z=1\) for small galaxies), they would lie on the local relation without invoking size evolution. It is not clear how truncation radius and half-light size are related, and our sample is significantly different from theirs, so it is not clear if our luminosity evolution is appropriate for these systems. It is, however, reassuring to
see a similar behavior in both samples (Trujillo & Pohlen and ours), small galaxies require more evolution than large ones.

Further investigations of the Barden et al. (2005) claim of inside-out disk growth should be made. For instance, it would be helpful to directly measure the spatial distribution of star formation in intermediate-redshift galaxies. Where are the dominant sites of star formation? Are they predominantly on the outskirts of galaxies with disks growing from the inside out? Are they smoothly distributed throughout the disks? Are they centrally concentrated, possibly driven by minor mergers and interactions? As galaxies become more bulge dominated they might drop out of the Barden et al. (2005) sample because of higher Sersic indexes. This might bias the Barden et al. measurement. We can learn something about the spatial distributions of star formation from the ACS $B$-band images that probe rest-frame UV. However, because much of the star formation can be dust-obscured, especially

Fig. 11.—TKRS number distributions in half-light radius (black) for three different luminosity classes and equal volume bins to $z = 1$. The magnitude bins were chosen such that the low-luminosity bin is complete out to $z = 0.9$. The red vertical lines at $R_{1/2} = 2.5$ and 5 kpc are drawn for comparison. There is no clear trend of increasing radius with time (at fixed magnitude) among galaxies in these luminosity classes. However, there is a decline in the number density, as illustrated by the lack of SDSS galaxies (red) in the most luminous bin, consistent with luminosity evolution rather than size evolution.
by $z = 1$, such studies might be biased against detecting centrally concentrated star formation. A better way of detecting the sites of ongoing star formation would be H$_\alpha$ imaging with a combination of HST ACS and NICMOS narrowband filters. H$_\alpha$ will be less obscured by dust than UV, allowing us to identify the major sites of star formation. Such a study would help us to understand how much inside out disk growth has occurred since $z = 1$. Unfortunately, such a data set does not currently exist.

5.2. Models of Luminosity Evolution

Accepting that significant luminosity evolution has occurred within the blue galaxy population, can we construct a simple, consistent model that describes the evolving stellar populations of these galaxies? For instance, is it possible for a stellar population to evolve by over 1.5 mag in luminosity without evolving in color to the red sequence? Figure 13 shows the $B$-band magnitude

![Fig. 12](image-url)
and B − V color evolution of three simple stellar population models with exponentially declining star formation rates (SFRs), or “tau models,” where tau gives the e-folding timescale for decline in SFR. The red model is effectively an instantaneous burst. The green curve is a tau model of exponentially declining star formation with \( \tau = 3 \) Gyr. The blue curve is effectively a constant star formation model. A timescale of 8 Gyr, roughly the amount of time between \( z = 1 \) and today, is marked off above the plot. Note that burst start time strongly affects the evolution measured for the instantaneous burst, but the extended evolution of the \( \tau = 3 \) model is less dependent on start time. Over the 8 Gyr timescale, the \( \tau = 3 \) model declines by \( \sim 1.6 \) mag and remains blue. This model is a reasonable explanation for the luminosity evolution of large and intermediate-sized TKRS galaxies. A shorter tau is necessary to describe the evolution of galaxies with smaller radii which appear to have evolved by \( \sim 2.5 \) mag since \( z = 1 \).

For small systems we need to invoke more complicated evolutionary scenarios than pure luminosity evolution. For instance, it is possible that the luminosity function shapes for small galaxies are not constant with redshift. We may be seeing a subset of galaxies experiencing a significant star burst rather than a brightening of the entire ensemble of small galaxies at high \( z \). The only way to determine the behavior for the entire ensemble of small galaxies is to study a sample that reaches fainter luminosities. This may be possible in the ultradeep field, but is beyond the scope of this paper.

The conclusion from the stellar population models in Figure 13 is that the assumption of nonevolving shape for the SDSS luminosity distributions for small galaxies is probably wrong. If we allow the shape to change then only a subsample of galaxies are experiencing large luminosity enhancements at high \( z \). The bursting dwarf systems seen at high redshift may fade significantly and are probably not the same objects that are bursting at lower redshift. Interestingly the small galaxies that happen to be bursting at high redshift achieve higher luminosities than the bursting galaxies at lower redshift. So some sort of evolution is taking place, either the intensity of the bursts or the frequency of the bursts has changed. The details of this evolution, however, are not well constrained by our data.
6. CONCLUSIONS

We measured the size and luminosity of 1440 galaxies from the Team Keck Redshift Survey of GOODS-N. Based on an analysis of the UDF and same region analyzed at the GOODS depth, we found that the GOODS field was not missing significant numbers of low surface brightness galaxies to the TKRS apparent luminosity limit. This indicates that previous studies of incompleteness in the deep HST survey fields, that were based on idealized model galaxies, may have over estimated the incompleteness. Blue galaxies at intermediate redshifts, $z \sim 1$, were easier to detect than smooth models because they usually contained substructure such as star-forming regions.

Our study of the blue galaxy population of TKRS revealed that the radius-luminosity relation has evolved since $z = 1$. The observed evolution is inconsistent with a pure radius evolution model, but it can be explained by a radius-dependent luminosity evolution. Assuming a linear decline in $B$-band magnitude, galaxies with large radii ($R_{1/2} > 5$ kpc) have evolved by $\Delta M_B(z = 1) = 1.53^{+0.13}_{-0.10}$. Intermediate-sized galaxies have experienced similar although slightly more evolution of $\Delta M_B = 1.65^{+0.08}_{-0.18}$. These declines in luminosity can be explained by a simple exponential decline in star formation. In particular an exponentially declining SFR with $\gamma = 3$ Gyr is a good match to the fading and SFR decline that is measured. Since pure luminosity evolution can explain the observations while a pure radius evolution cannot, it is reasonable to assume that luminosity evolution dominates. This does not, however, preclude some moderate size growth, in which case we have measured upper limits to the luminosity evolution.

Small galaxies ($R_{1/2} < 2.5$ kpc) appear to have undergone significantly more evolution, $\Delta M_B = 2.55 \pm 0.38$, almost a factor of 10 in luminosity, and different from larger galaxies at the 2 $\sigma$ level. This sharp decline in luminosity cannot be explained by a simple exponential decline in star formation in the entire small galaxy population. Tau models would predict a decline of roughly 1000 in SFR if the decline in luminosity were happening uniformly to the entire sample over the last 8 Gyr. Because small blue galaxies are sites of significant star formation today, this scenario does not work. The luminosity decline can, however, be explained by a subpopulation of bursting dwarf systems at high redshift that have faded by the current epoch. Such a population has been previously identified as luminous, compact, blue galaxies that are rare locally but were relatively common by $z = 1$. The measured evolution could then be a result of a change in the intensity or frequency of bursts.

We would like to thank Luc Simard for providing the local SDSS sample; Jay Strader and Chien Peng for key insightful comments; the DEEP team for long discussions of the project; and Jason Prochaska and Yasmin Lucero for help with statistical tests.

This work was supported in part by the NSF Science and Technology Center for Adaptive Optics managed by UC Santa Cruz under the cooperative agreement AST 98-76783. Partial funding came from the DEEP2 program supported by NSF grants AST 00-71198, AST 05-27930, and AST 00-71048. Partial funding also came from the HST archival grant HST-AR-009946.

This work used observations from the NASA/ESA Hubble Space Telescope obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Redshifts came from the DEIMOS spectrograph funded by a grant from CARA (Keck Observatory), an NSF Facilities and Infrastructure grant (AST 92-2540), the Center for Particle Astrophysics, and gifts from Sun Microsystems and the Quantum Corporation. These data were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. We also wish to recognize and acknowledge the highly significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community.

REFERENCES

Alexander, D. M., et al. 2003, AJ, 126, 539
Barden, M., et al. 2005, ApJ, 635, 959
Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, ApJ, 498, 504
Bell, E. F., et al. 2004, ApJ, 608, 752
Bershady, M. A., Višn, M., Hooy, C., Guzmán, R., & Koo, D. C. 2005, in Starbursts: From 30 Doradus to Lyman Break Galaxies ed. R. De Grijs & R. M. Gozdzac Delgado (Dordrecht: Springer) 77
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Blanton, M. R., et al. 2003a, ApJ, 592, 819
———. 2003b, ApJ, 594, 186
Bouwens, R., & Silk, J. 2002, ApJ, 568, 522
Faber, S., et al. 2005, ApJ, in press (astro-ph/0506044)
Floc'h, E., Rocco-Volmerange, B. 1997, A&A, 326, 950
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Fukugita, M., Shimasaku, K., & Ichikawa, T. 1995, PASP, 107, 945
Giavalisco, M., et al. 2004, ApJ, 600, L93
Guzmán, R., Gallego, J., Koo, D. C., Phillips, A. C., Lowenthal, J. D., Faber, S. M., Illingworth, G. D., & Vogt, N. P. 1997, ApJ, 489, 559
Guzmán, R., Østlin, G., Kunth, D., Bershady, M. A., Koo, D. C., & Pahre, M. A. 2003, ApJ, 586, L45
Hopkins, A. M., Schulte-Ladbeck, R. E., & Drozdovskiy, I. O. 2002, AJ, 124, 802
Kendall, M., Stuart, A., & Ord, J. K. 1987, in Kendall’s Advanced Theory of Statistics, Vol. 1 (Oxford: Oxford Univ. Press), 284
Kennicutt, R. C. 1998,ARA&A, 36, 189
Koo, D. C., Guzmán, R., Faber, S. M., Illingworth, G. D., Bershady, M. A., Kron, R. G., & Takahara, M. 1995, ApJ, 440, L49
Krist, J. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R.A. Shaw, H.E. Payne, & J.J.E. Hayes (San Francisco: ASP), 349
Le Floc’h, E., et al. 2005, ApJ, 632, 169
Lilly, S., et al. 1998, ApJ, 500, 75
Melbourne, J., Koo, D. C., & Le Floc’h, E. 2005, ApJ, 632, L65
Phillips, A. C., Guzmán, R., Gallego, J., Koo, D. C., Lowenthal, J. D., Vogt, N. P., Faber, S. M., & Illingworth, G. D. 1997, ApJ, 489, 543
Ravindranath, S., et al. 2004, ApJ, 604, L9
Shen, S., Mo, H. J., White, S. D. M., Blanton, M. R., Kauffmann, G., Voges, W., Brinkmann, J., & Csabai, J. 2003, MNRAS, 343, 978
Simard, L. 1998, in ASP Conf. Ser. 145, Astronomical Data Analysis Software and Systems VII, ed. R. Albrecht, R. N. Hook, & H. A. Bushouse (San Francisco: ASP), 108
Simard, L., et al. 1999, ApJ, 519, 563
Somerville, R. S., Primack, J. R., & Faber, S. M. 2001, MNRAS, 320, 504
Trujillo, I., & Aguerri, J. A. L. 2004, MNRAS, 358, 82
Trujillo, I., & Pohlen, M. 2005, ApJ, 630, L17
Weiner, B. J., et al. 2005, ApJ, 620, 595
Werk, J. K., Jangren, A., & Salzer, J. J. 2004, ApJ, 617, 1004
Williams, R. E., et al. 1996, AJ, 112, 1355
Willmer, C., et al. 2006, ApJ, 647, 853
Wirth, G. D., et al. 2004, AJ, 127, 3121