FERENGI: REDSHIFTING GALAXIES FROM SDSS TO GEMS, STAGES, AND COSMOS

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ABSTRACT

We describe the creation of a set of artificially “redshifted” galaxies in the range 0.1 < z < 1.1 using a set of ~100 SDSS low-redshift (v < 7000 km s⁻¹) images as input. The intention is to generate a training set of realistic images of galaxies of diverse morphologies and a large range of redshifts for the GEMS and COSMOS galaxy evolution projects. This training set allows other studies to investigate and quantify the effects of cosmological redshift on the determination of galaxy morphologies, distortions, and other galaxy properties that are potentially sensitive to resolution, surface brightness, and bandpass issues. We use galaxy images from the SDSS in the u, g, r, i, and z filter bands as input, and computed new galaxy images from these data, resembling the same galaxies located at redshifts 0.1 < z < 1.1 and viewed with the Hubble Space Telescope Advanced Camera for Surveys (HST ACS). For this process we take into account angular size change, cosmological surface brightness dimming, and spectral change. The latter is achieved by interpolating a spectral energy distribution that is fit to the input images on a pixel-to-pixel basis. The output images are created for the specific HST ACS point-spread function and the filters used for GEMS (F606W and F850LP) and COSMOS (F814W). All images are binned onto the desired pixel grids (0.03″ for GEMS and 0.05″ for COSMOS) and corrected to an appropriate point-spread function. Noise is added corresponding to the data quality of the two projects, and the images are added onto empty sky pieces of real data images. We make these data sets available on our Web site, as well as the code—FERENGI (Full and Efficient Redshifting of Ensembles of Nearby Galaxy Images)—to enable data sets for other redshifts and/or instruments to be produced.

Subject headings: galaxies: fundamental parameters — galaxies: high-redshift — galaxies: structure

Online material: color figures

1. INTRODUCTION

In the current era of observational astronomy, the size of galaxy data sets means that number statistics start to lose its spot as the number-one source of uncertainty in galaxy-evolution studies. With the availability of large wide-field galaxy surveys such as the Sloan Digital Sky Survey (SDSS; York et al. 2000) or the Two Degree Field Galaxy Redshift Survey, and the deep, space-based high-resolution projects like the Hubble Ultra Deep Field, GOODS, GEMS, and STAGES projects and the Cosmic Evolution Survey (COSMOS) with their 10⁶–10⁷ galaxies, other error sources become vital to understand.

If we want to understand the buildup of galaxies with their intricately linked evolution in stellar and black hole mass, luminosities, colors, morphological types, and the alternations between interaction and relaxation, we have to understand what the tools we apply really measure. Any given galaxy will look different when viewed with different instruments or when located at different redshifts, due to cosmological dimming and changes in rest-frame bandpass.

This makes the qualitative or quantitative classification of, for example, galaxy morphology nontrivial to compare over different redshifts or filters. As one example, faint disks visible at one redshift will fade from the observer’s view at larger distances, not only affecting eyeball classifications of morphology but also automatic classifier software. Moreover, low surface brightness signs of interaction and structures, such as bars that are not prominent in the rest-frame ultraviolet, will not be visible at higher redshifts.

If the evolution of galaxies is to be studied via merger statistics, morphology-segregated evolution, star formation histories, and type-specific luminosity functions, all morphological classifiers have to be calibrated in order to deliver comparisons of similar quantities at all redshifts, taking into account bandpass-dependent properties and changes in signal-to-noise ratio (S/N).

From the analysis of HST survey data we know that the average surface brightness of the disk galaxy population fades with time (e.g., Lilly et al. 1998; Barden et al. 2005). The change is approximately 1–1.5 mag depending on rest-frame bandpass over the redshift interval 0 < z < 1. To some degree this surface brightness evolution counters the cosmological dimming and helps detect low surface brightness features. Thus, if this effect is not taken into account, predictions about the recoverability of structural parameters or classifications are overly pessimistic.

For a few projects in the past, codes were created that would include some of these effects for specific applications or data sets (e.g., Abraham et al. 1996a, 1996b; Giavalisco et al. 1996; Bouwens et al. 1998; Takamiya 1999; Burgarella et al. 2001; Kuchinski et al. 2001; van den Bergh et al. 2002; Lisker et al. 2006). However, to our knowledge no codes or data sets that include geometrical and cosmological bandpass shifting effects are currently publicly available. In this article we describe the creation of artificial image data sets in the range 0.1 < z < 1.1, computed from low-z SDSS galaxies by artificial “redshifting.” Since we refrain from adding any evolutionary models but purely apply cosmological changes in angular size, surface brightness and filter bandpass, this data set shows exactly how such galaxies will appear when observed from cosmological distances, at which redshift certain features become undetectable, and any quantitative classifier procedure can be tested for dependency on redshift effects.

Our code, FERENGI, and the current data sets were originally created for the morphological classification of active and inactive

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galaxies in the GEMS (Rix et al. 2004), STAGES (M. Gray et al. 2008, in preparation), and COSMOS (Scoville et al. 2007) projects. The data sets for the HST ACS image characteristics of the GEMS and COSMOS project are freely available from our Web site.3 As many studies might benefit from such data, we also make the FERENGI code available on the same Web page for others to use with different input samples, redshifts, and instrument characteristics.

We describe the input data in §2; the redshifting procedure, including the basic cosmological formulae involved and the bandpass shift in §3; and the creation of realistic images from this information in §4, including example results (§5). Next, we present a series of tests characterizing the robustness and accuracy of the code (§6). In §7 we discuss limitations of this procedure. All examples and cosmology-dependent numbers given here are computed assuming a flat universe with ΩM = 0.7 and h = H0/(100 km s−1 Mpc−1) = 0.7.

2. INPUT GALAXY SAMPLE

The basic idea is to convert images of well-resolved, low-redshift galaxies to images simulating the same galaxies at higher redshift. Input and output images can differ in assumed redshift, pixel size, point-spread function (PSF), and noise properties. We explicitly compute two versions, with and without luminosity/surface brightness evolution terms. When purely considering instrumental and cosmological effects, users of such data sets can apply his or her tools to the exact same galaxies, but located at different redshifts for calibration purposes. When including evolution, more realistic galaxies are created. For the current study we have implemented a linear scaling with redshift to make sources brighter at high redshift.

For this project we require input galaxy data with two main properties:

1. Sufficient sampling.—The combination of distance to the galaxy, pixel size, and width of the PSF must be sufficient for the target pixel size and PSF width at the lowest target redshift (e.g., z ≥ 0.1).

2. Information about the spectral energy distribution.—The task needs homogeneous multiband imaging, used for interpolation between filters to compute fluxes in the target filter band at the desired redshift without extrapolation.

The best source for such data is nearby galaxies from the SDSS. This survey provides imaging data in its own u, g, r, i, and z filters with 0.396 pixel−1 sampling. We compute the maximum distance for input galaxies from the two requirements to (1) simulate images with 0.05′′ and 0.03′′ pixel size at a minimum redshift of z = 0.1 and (2) have an output PSF not already broader than the ~0.096′′ (FWHM) PSF of the ACS Wide Field Channel (WFC) drizzled images in the F606W or F814W filters. Figure 1 shows the resulting limit in cz and the limit from the width of the PSF for a sample of SDSS galaxies and their PSF conditions. Both criteria select a similar set of galaxies, corresponding to limiting recession velocities of v ≤ 2000, 3700, and 5000 km s−1 for zout,min = 0.1, 0.2, and 0.3, respectively, and 0.03′′ output pixel size. For pixel size 0.05′′ the limits change to v ≤ 3400, 6200, and 8400 km s−1.

These technical aspects define the boundary conditions of our sample selection. We emphasize that at this point we do not aim to select a sample that is complete or representative for the general population of galaxies in a statistical sense. The sample selection only intends to span a large range of morphological types and common features, targeting large, rather luminous galaxies that could still be observed at larger z.

With this intention we make a selection of galaxies from the SDSS survey area, via the HyperLeda (Paturel et al. 1989; Prugniel & Heraudeau 1998) catalog facility, with the following parameters: recession velocity 200 ≤ vz ≤ 7000 corrected for Virgo infall (208 km s−1)z, apparent isophotal diameter D25 ≥ 1′, and apparent magnitude BT ≤ 16, and added a total B-band magnitude cut at MB ≤ −19.5.

Images were taken from Data Release 4 (DR4) of the SDSS (Abazajian et al. 2005). As the SDSS imaging data is not targeted on individual galaxies, a fraction of about 40% of the selected galaxies extends beyond the borders of the 680 × 590 arcsec2 SDSS field of view. We excluded such galaxies as input after visual inspection.

In total we selected a sample of 96 galaxies with cz < 7000 km s−1 and very heterogeneous morphologies. Figure 2 shows the Hubble diagram of the input sample. In the same figure and in Table 1 we give the distribution of morphological classification according to the Third Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al. 1991) to illustrate the sample composition. Note that the class “peculiar” was manually selected for showing signs of ongoing mergers, or close or overlapping galaxies.

As in the local universe, few galaxies show strong signs of interactions or even mergers; we gradually extended our selection range from 500 < cz < 3000 out to cz < 7000. At larger distances we only included “peculiar”-looking sources such as strong interactions or mergers. However, we also included some unrelated objects that have small projected radii or even overlap. Our intention here was to demonstrate the increasing difficulty at
high redshift to morphologically discern interaction from projection effects.

3. REDSHIFTING PROCEDURE

The FERENGI redshifting procedure has two components: cosmological angular size and surface brightness changes on one side, and bandpass shifting on the other. After computation of these cosmological effects, we correct for PSF effects and add noise.

3.1. Angular Size and Surface Brightness

When converting from an input image with pixel size $p_i$ of a galaxy at redshift $z_i$ to an output redshift $z_o$ and desired pixel size $p_o$, both angular sizes and surface brightnesses have to be modified for distance and cosmological effects. Using $\tan (a) = a$ for small angles, the angular size $a$ of a given linear dimension changes as

$$a_o = a_i \frac{d_i}{d_o (1 + z_o)^2}$$

with the luminosity distance $d$. Since the input image will be rebinned to the output pixel size, angular sizes in units of pixels $n$ and thus image rebinning factors are

$$\frac{n_o}{n_i} = \frac{d_i}{d_o (1 + z_o)^{2}} \frac{p_i}{p_o}$$

The flux in each pixel is subject to surface brightness dimming. If we require the galaxy absolute magnitude to be conserved,

$$M = m_i - 5 \log (d_i) - c = m_o - 5 \log (d_o) - c,$$

we find a relation for the ratio of observed fluxes $f$ of the input and output images,

$$2.5 \log \left( \frac{f_o}{f_i} \right) = m_i - m_o = 5 \log \left( \frac{d_i}{d_o} \right) + \frac{(d_i)^2}{(d_o)^2},$$

which gives the standard bolometric surface brightness dependence of $(1 + z)^{-4}$. The finite filter width is taken care of in the next component.

Note that in order to account for the bandpass shift it is imperative to match object positions in the input images. This matching is a complex process that potentially includes shifting, rotation, and scaling of the input data. Moreover, the PSFs of the data should match. In the case of strongly varying PSFs, color terms may be introduced in the bandpass shifting. When combining, for example, GALEX and SDSS data, to extend the wavelength baseline to the UV, the users would have to prepare the input image accordingly. They have to shift all images to a common position, scale the GALEX image to the SDSS pixel scale, possibly rotate the GALEX image to match the SDSS frame, and smooth all SDSS images to the GALEX FWHM. These images are then input to FERENGI. Thus, preparing the input appropriately, FERENGI is not limited in the combination of telescopes, filters, or instruments.

3.2. Bandpass Shift

While the above rebinning and flux rescaling take care of all geometrical effects, bandpass shifting and stretching still have to be added. The cosmological redshift will (by definition) shift the observed rest-frame bandpass for a given observing filter as a function of redshift, as well as change the size of a given filter. In addition, we want to have the option of producing images for a range of optical observed filters.

For this task we input spectral information in the form of multiband imaging. A combination of observer filter and redshift defines the desired rest-frame filter curve. For each pixel of the input frame we calculate the expected flux for this rest-frame filter by interpolating between multiband information on this pixel. This task is facilitated by the routine $k\_\text{correct}$ (ver. 4.14; Blanton et al. 2003; available for IDL and C) that was written to fit spectral templates to a set of multiband images. We use $k\_\text{correct}$ to determine a best template for individual pixels in an image, and from this the flux in each pixel for a given filter. We thus construct a rest-frame filter image. This bandpass shift and the above size rebinning are interchangeable in order. To minimize the computational effort and to reduce noise, we first recomputed the (coarser) redshifted images and then applied the bandpass shift. In addition,
only pixels with flux exceeding 2 times the rms of the background are input to k-correction (optional feature). The remaining pixels receive a flux-weighted K-correction computed from the bright pixels. While this could become more important at low-S/N levels, it showed not to have a significant effect on the currently chosen bright sample of galaxies.

Note that the template set incorporated in k-correction stems from (Bruzual & Charlot 2003) models. These model templates cover the rest-frame wavelength range from UV to IR (600 Å to 320 µm). As long as the input filters together with the targeted output redshift fall within this range, any combination is possible.

4. POINT-SPREAD FUNCTION AND NOISE

Two essential ingredients for realistic images are (1) to mimic the resolution of the real data by convolution with an appropriate PSF and (2) to generate realistic noise levels for galaxy and background. The input SDSS galaxies were observed under varying seeing conditions, with an average PSF width of 1.4″ FWHM corresponding to ~3.5 SDSS camera pixels. After application of the redshifting procedure, the intrinsic PSF is of finite width and non-negligible. While for point or composite sources such as type I AGNs, the detailed knowledge about the PSF is essential, the requirements are not as stringent for extended galaxies. However, as the simulated data set is meant to calibrate quantitative morphological analysis methods and programs, it is important to create a PSF that is sufficiently similar to the real PSF for the task in question.

In light of this we attempt to reach a final PSF that is as close as possible in shape and width to the ACS PSF in the desired band. This involves the creation of a convolution kernel that will produce the ACS PSF shape from the input PSF shape. As the width and geometric shrinking of the PSF depends on both input and target redshift, and the input PSF varies, this kernel needs to be recomputed for each input galaxy and output redshift. This is done by a transformation into Fourier space, suppression of noise by Wiener filtering, and subsequent division of the spectra of the two PSFs. After transformation of this quotient back into the spatial domain, we receive the function that is needed to convolve the input image to reach a PSF close to the ACS PSF. This is mathematically equivalent to a deconvolution of the output PSF with the desired input PSF. For the comparably high S/N PSF in these data, this works fairly well. Note that the filter of the input PSF is chosen from the set of SDSS filters minimizing the wavelength difference to the desired rest-frame band, thus also minimizing color gradients in the reconstructed PSF. However, the seeing is wavelength dependent and can also vary on the short timescales between the integration in the different SDSS filter bands. This can still result in small differences between the actual PSF present for a reconstructed galaxy image and the reconstructed PSF image. In order to remove this wavelength dependency, we choose a well-sampled and not saturated star in each SDSS filter as PSF. We convolve the SDSS images with a kernel (as described above) that generates a round Gaussian PSF with a FWHM for all filters of 1.1 times the largest extent of the input PSFs. Thus, PSF resolution effects and color gradients are kept at an absolute minimum. A comparison of the reconstructed and target ACS PSF shows a difference of less than 0.1% in each individual pixel.

This procedure is limited to cases where the widths of input and output PSFs are sufficiently different. If not, noise will introduce artifacts as ringing patterns or mathematical ghost images near bright sources, which is clearly not desirable. This occurs primarily when the input PSF resolution becomes comparable to the output PSF width (i.e., at the low-redshift end), so the convolution function becomes very narrow.

In order to facilitate proper modeling of the redshifted galaxy images, we discourage the use of the publicly available GEMS or COSMOS PSF, but suggest using the reconstructed PSF instead. Although this might not be crucial for determining two-dimensional galaxy light profiles, it could make a significant difference in the case of AGNs and their host galaxies. Likewise, we recommend using scaled versions of the reconstructed PSF to be put on top of redshifted galaxy images in order to create artificial AGNs.

Noise in the output images has two main sources: sky background and the galaxy flux itself. For one-orbit exposures as in COSMOS and GEMS, the sky background noise dominates over the readout noise (~5.2 e− for the ACS WFC) after a few 100 s of integration, in the case of broadband filters. Thus, the latter is negligible. In addition, at 0.0022 e− s−1, the ACS WFC dark current does not play a significant role.

The background noise in our simulations is not created from random numbers, but the noise-added galaxy images are added onto blank sky taken from the observed data itself (for ACS data reduction for GEMS and COSMOS, see Caldwell et al. 2008; Koekemoer et al. 2007). In this way, reduction signatures such as correlated noise and intrinsic small variations in the otherwise empty regions of the sky are also present in the simulated data. We extract several 60″ square fields from the data. While we choose comparably empty regions of the sky, the ACS is so efficient over one orbit for both the COSMOS and GEMS filters that there exists no “empty” sky over more than 10″–20″ regions. To remove prominent remaining objects, we replace the corresponding pixel regions with unique other small patches of blank sky. This process does not involve any filtering, only replacing. In this way the resulting empty sky fields are very good random representations of empty sky regions. If for an application the sensitivity of a measurement to small residual background/foreground objects is to be tested, the user can add his/her favorite contamination or even use random patches of uncleaned sky as background.

Noise has to be added also to the redshifted galaxy images themselves. The S/N per pixel of the input galaxies is high by definition of the sample. After redshifting and PSF adaptation, their photon noise is negligible compared to the noise expected from a single-orbit HST/ACS exposure. The resulting images are scaled in flux corresponding to, for example, 2028 s (COSMOS) integration time, in the respective output filter. The galaxy image—in units of electrons per pixel—then has random Poisson noise added, with a σ² corresponding to the galaxy flux per pixel. Subsequently, the galaxy is added on top of the empty background images. In a statistical sense this procedure is not strictly correct, as the photon noise addition should be applied to the sum of sky and galaxy, but cannot be avoided if real sky images are to be used. However, the resulting higher noise only appears in regions of the final image where sky background and galaxy contribute equally in noise: in the faint isophote regime of the galaxy.

5. RESULTING GALAXY IMAGES

Artificially redshifted galaxies are created for a redshift range out to z = 1.1. The starting redshift was taken for each galaxy, either z = 0.1 or the minimum redshift at which both input PSF width and pixel size begin to match the output PSF and pixel size. We give images for steps of Δz = 0.05 out to z = 0.5 and Δz = 0.1 beyond that, thus a maximum of 15 output redshifts per input galaxy.

Simply shifting local galaxies out to high redshift makes them look rather faint compared to real average galaxies at such distances. In order to reflect the brightness increase of high-redshift
Fig. 3.—Redshifting examples. From left to right, the first four panels in each row show the original SDSS $gri$-color composite image and the redshifted GEMS $F606W$–$F814W$ false color images at $z = 0.15$, 0.45, 0.5, and 1.0. The fifth column includes magnitude evolution by $\Delta m = -1(z)$ mag at redshift $z = 1$. Apparent scales are indicated in each panel; physical scales are the same in each panel and therefore only marked in the leftmost panel. [See the electronic edition of the Supplement for a color version of this figure.]
sources, we put in a crude mechanism to introduce evolution. This optional feature allows us to make galaxies brighter as a linear function of redshift,

\[ M_{\text{evo}} = xz + M. \]

Setting \( x = -1 \) would make a galaxy 1 mag brighter at redshift \( z = 1 \) than it would normally be. Yet this option is not meant to be a substitute for real morphological or photometrical evolution and does not replace stellar evolution codes. The reason for putting in such a simple functional form is the application of galaxy classification by eye. If one is to reidentify galaxies shifted to high redshift, the task is made increasingly unfair compared to classification by eye. If one is to reidentify galaxies shifted to high redshift, if one does not apply artificial brightening.

In order to demonstrate the accuracy of FERENGI and characterize its limits, we perform a number of tests. We use the program GALFIT (Peng et al. 2002) to determine structural parameters, which is often used for parameter estimation and morphological classification of galaxy samples, particularly in survey applications. The program is (potentially) susceptible to S/N changes and morphological K-correction, like any other fitting code. Yet, Häußler et al. (2007) have shown that GALFIT is very robust and does not exhibit systematic biases when fitting radial surface brightness models to artificial two-dimensional Sérsic-type\(^4\) light profiles. In § 6.1 we make use of this robustness and apply GALFIT to various sets of simulated two-dimensional Sérsic profiles to determine the dependence of structural parameters on the application of FERENGI.

In addition to GALFIT we use a code described in Häußler et al. (2007) to create two-dimensional Sérsic profiles mimicking our observed galaxies. This procedure features a fine subsampling of the inner pixels, allowing highly accurate flux calibration. Convolving is done with the original PSF as reconstructed from the SDSS, after smoothing the individual five bands to a round Gaussian configuration. Poisson noise and a real SDSS sky background image are added. Such simulated images are created for all five SDSS bands: \( u, g, r, i, \) and \( z \).

### 6.1. Procedure for Individual Galaxies

We conduct the simulations in six different steps in order to check for possible systematics introduced at each step. The summary of each step is shown in Table 2. We show by way of illustration an example of an elliptical galaxy (Fig. 4). It has an almost de Vaucouleurs–type light profile (\( n \) increases from 3.2 to 3.6 going from \( u \) to \( r \) band). The size of the galaxy is constant across the three bands; the magnitude covers a range of over 2.5 mag, with \( u \) being faintest and \( r \) brightest, as expected for a red elliptical.

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\( ^4 \) The Sérsic profile is a generalized exponential profile, with one parameter, \( n \). For \( n = 1 \) the profile is a simple exponential curve, typical of disk galaxies; for \( n = 4 \) the profile becomes a de Vaucouleurs exponential \( r^{1/4} \) profile.
1. We start by using GALFIT to fit a Sérsic profile to the set of SDSS images belonging to the objects. This provides the basis for simulating the smooth model images.

2. With the GALFIT parameters, we create artificial model images using the procedure by Häu
ter et al. (2007) described above, resembling smooth versions of the SDSS galaxy images. A fit to these smooth images in all bands confirms the stability of the process by retrieving almost exactly the input values.

3. Next we create artificial model images of the same galaxies, as they would appear at high redshift (our set of output redshifts given in § 5) using the parameters from before, in the $u$, $g$, and $r$ bands. We do not apply FERENGI here, but only convert the linear scales according to redshift. This will quantify the response of GALFIT to the decreasing S/N as a result of cosmological surface brightness dimming.

4. Figure 5 demonstrates how GALFIT performs as a function of redshift for the example galaxy (No. 2 from Table 2). The higher the redshift, the lower is the S/N of the object and its surface brightness. Quite expectedly, the quality of the recovered fit parameters degrades with redshift. As the $u$ band has the lowest S/N of all SDSS filters, GALFIT fares worst there; the $r$ band behaves best, having the highest S/N. The chosen galaxy being rather red, this effect is even amplified. As the galaxy is rather bright, overall, the deviations in the parameters from their input values are rather small. In order to allow a comparison with GEMS, we compute the average apparent surface brightness of our sample galaxies with $3 < n < 5$ in $u$, $g$, and $r$. From Häu
ter et al. (2007) we obtain the corresponding GALFIT errors in GEMS. The results are listed in Table 3.

5. Now we use FERENGI on the simulated smooth $u$-, $g$-, and $r$-band model images to create versions of these images that are appropriate for higher redshifts. We use the Sérsic fits to this set of images to determine the influence of conversion to a new pixel grid and related PSF on different galaxy parameters, as a function of redshift. Note that the $K$-correction code is disabled for this purpose. The image set contains the flux of the SDSS filters transformed to a new pixel size, PSF, background noise properties, and the cosmological effect of surface brightness dimming.

For the example galaxy, the left-hand side of Figure 6 shows the same as Figure 5; the right-hand side has the values from Figure 5 subtracted in order to indicate the extra influence of the regridding process. We find no additional systematics, and the scatter hardly increases.

6. After that we enable $K$-correction, thus fitting an SED to all five SDSS bands and extracting the flux at the position of the observed ACS filter, in addition to the downscaling and surface

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**TABLE 3**

| $z$ | Band | $M$ (mag) | $R_e$ (%) | $n$ (%) |
|-----|------|----------|----------|--------|
| 0.2 | $u$  | 0.05 ± 0.42 | −0.06 ± 0.41 | −0.03 ± 0.27 |
|     | $g$  | 0.01 ± 0.15 | 0.00 ± 0.22 | −0.01 ± 0.21 |
|     | $r$  | 0.01 ± 0.13 | 0.00 ± 0.20 | −0.01 ± 0.20 |
| 0.4 | $u$  | 0.10 ± 0.50 | −0.08 ± 0.48 | −0.05 ± 0.28 |
|     | $g$  | 0.02 ± 0.20 | −0.01 ± 0.27 | −0.01 ± 0.22 |
|     | $r$  | 0.01 ± 0.17 | 0.00 ± 0.24 | −0.01 ± 0.21 |
| 0.8 | $u$  | 0.18 ± 0.61 | −0.15 ± 0.50 | −0.06 ± 0.31 |
|     | $g$  | 0.03 ± 0.32 | −0.04 ± 0.35 | −0.02 ± 0.26 |
|     | $r$  | 0.02 ± 0.27 | −0.03 ± 0.32 | −0.02 ± 0.25 |

**Notes.**—The morphological parameters of the average galaxy with $3 < n < 5$ in our sample are $M = [−19.53, −21.09, −21.95], R_e = [12.0, 7.7, 9.9]$ in $[u, g, r]$. Indicated errors are $1 \sigma$ from the mean.
brightness dimming. This provides a set of images representing the simulated SDSS galaxies as they would look at high redshift, including all cosmological effects (No. 4 from Table 2).

The result for the example galaxy is shown in Figure 7. In the top panels we plot the original input values. Also shown are the fit values from using the $K$-correction code. In order to provide a rough estimate of the deviation from the expected values, we fit the five values from the simulated SDSS images with a polynomial and subtract this fit. Going into all the details of modeling galaxy photometry and structure in multiple wave bands (or even continuously) is well beyond the scope of this paper. Therefore, we regard the lower panel not as a proper estimate of the error budget, but rather an indication of systematic trends. Points missing from the lower panel were left out in order to not overstretch the plotting axis and to focus on the main region of interest.

Finally, we run FERENGI on the real SDSS images, including $K$-corrections (No. 5 from Table 2). The GALFIT results for this series reveal, compared to the redshifted simulations (No. 4 from Table 2), the impact of morphology on the whole process (see Fig. 8).

As the performed calculations are virtually identical, any differences in the output must result from irregularities in the real data, such as tidal features, spiral arms, and dust lanes. The example galaxy was chosen to be rather featureless. Therefore, a perfect match is obtained. Yet in the majority of cases we find systematic differences: either redshift-dependent deviations (originating from irregularities) or global shifts toward higher or lower values. At the highest redshift ($z \sim 1$) the impact of morphology might decrease again, as virtually all features are smeared out.

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**Fig. 7.**—Performance of FERENGI (for an example galaxy); $K$-correction enabled. *Top:* Turning on $K$-corrections, we compare the absolute magnitudes, half-light radii, and Sérsic indices of the simulated SDSS images (filled circles), which were used as input for the redshifting, directly with the redshifted output (open circles). The solid line marks a polynomial fit to the input data. *Bottom:* Subtracting the polynomial fit from the output data. [See the electronic edition of the Supplement for a color version of this figure.]

**Fig. 8.**—Comparison of reality and simulation (for an example galaxy). Plots for magnitude, half-light radius, and Sérsic index, from top to bottom. Simulated data shown as circles; real data as plus signs. Filled circles indicate local input data. *Left:* Absolute quantities. The solid line shows a polynomial fit to the simulated data. *Right:* Polynomial fit subtracted from the data. Hardly any difference is visible, indicating that the input galaxy fits well the featureless Sérsic profile. [See the electronic edition of the Supplement for a color version of this figure.]
Yet the reason for global offsets is of a technical nature: the drastic change in resolution and depth when transforming a low-redshift image (cz of a few thousand km hr\(^{-1}\)) to high redshift (z \(\cong 0.1\)) results in the rebinned PSF not being Nyquist-sampled any more. This causes shifts when performing Fourier transformations. The effect is more pronounced at low (z \(\cong 0.1\)) than at high (z \(\sim 1\)) redshift, because eventually the PSF becomes pointlike.

6.2. Average Results

We applied FERENGI to all 96 sample galaxies. This allows us to quantify systematic biases of the redshifting code in some detail. In Figure 9 we show the average deviation from the input values for simulations of high-redshift galaxies and downscaled versions of simulated galaxies (Nos. 2 and 3 from Table 2). The errors and systematic offsets are not significantly different. For the given observational setup (redshifting of SDSS images to COSMOS and GEMS) roughly at z \(\sim 0.7\), larger deviations in particular in u band occur. Note that these departures from the expected mean are seen in the simulated images as well. Therefore, they must originate from the specific GALFIT setup, but not from FERENGI itself.

In order to compare the results of the high-redshift simulations and the downsampling-only simulations (Nos. 2 and 3 from Table 2) with the K-corrections-enabled setup (No. 4), we plot as a function of redshift the measurements in the SDSS filters closest to the rest-frame ACS filter (Fig. 10). It is interesting to note that the error bars in the right panel of Figure 10 (No. 4) at the highest two redshift bins are smaller than without K-corrections (No. 3) or even in the pure simulations (No. 2). The reason for this is that the SED fitting uses all five SDSS bands and therefore introduces some information extrapolated from g, r, i, and z (the closer bands being weighted more strongly than the redder bands) to improve the low S/N u-band data. However, this implies also that template mismatches might change the morphological appearance of the object to some extent. As the SED-fitting code is deeply embedded in k_correct, we do not attempt to characterize the impact any further. Moreover, we find that the K-correction code on average introduces stronger fluctuations and increases the error bars slightly at lower redshifts. Systematic deviations to lower brightnesses, radii, or Sérsic indices are not statistically significant.

7. DISCUSSION AND CONCLUSIONS

We discern from Figures 9 and 10 that FERENGI has no unwanted systematic effects on measured morphological and photometrical parameters of simulated galaxies. The deviations from theoretical values are well within the uncertainties expected from, in this case, GALFIT, also in absolute terms. Both linear scales and magnitudes are well reproduced. This includes the bandpass shifts induced by redshifting and different filters, as is demonstrated in the right panels of Figure 10. The k_correct module correctly interpolates between input filter images. We cannot exclude issues when extrapolating k_correct templates, but we explicitly restrict the output range of redshifts to only use template interpolation, between bands.

We make FERENGI publicly available from our Web page, as well as redshifted sets of images for redshifts 0.1 \(\leq z \leq 1.1\) and different HST ACS filters. Primarily, these are created for the GEMS (F606W and F850LP at 0.03\(^{\prime\prime}\) pixel\(^{-1}\)) and COSMOS (F814W at 0.05\(^{\prime\prime}\) pixel\(^{-1}\)) projects, but the code can be modified and used for other filters. The user can extend the input sample of images (also provided on the Web page) to other objects, filter curves, and output redshifts, and in principle also to other data sources. We leave it up to the user to update FERENGI with respect to the K-correction module when including other input filter bands.

As stated, templates are used for interpolation between input filters. They can theoretically also be extrapolated beyond the input-wavelength interval, if one has faith in the templates. However, we strongly advise against this for a different reason. Because of the limited S/N available for the pixel-by-pixel K-correction that is computed, a mild extrapolation might be acceptable, but the noise of the output pixels and systematic deviations will obviously increase with distance to the last supported wavelength. As various templates might be degenerate when interpolating, there might be striking differences on extrapolation, resulting in large errors in the output flux.

As a second caveat we note that stars in the input images are not treated separately in FERENGI or in the provided data sets. Any flux in the input images, be it stars or background/foreground galaxies, will be treated as if it were at the distance of the target and thus will be redshifted. While distant background galaxies usually disappear, stars will be represented with the output PSF, resembling a faint, dense star field (the density of stars is enhanced quadratically with decreasing linear scales as the simulation redshift increases). Of even greater concern are foreground (or closer background) galaxies. In the output, their physical properties are calculated falsely, as their assumed distance is not correct. Whether the resulting images will in the end be reliable representations of reality strongly depends on the quality of input images, the type of galaxies, and their correspondence with the templates used.
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Fig. 10.—Average deviations from the input values including K-corrections. Panel lines show absolute magnitude difference, ratio of measured and input half-light radius, and Sérsic index; panel columns show simulation of high-redshift galaxies, redshifting of simulated galaxies without K-corrections, and redshifting of simulated galaxies with K-correction enabled (Nos. 2, 3, and 4 of Table 2, respectively). The error bars are robust, 1 σ from the mean. The leftmost two panel columns show data from Fig. 9. In contrast to Fig. 9, we choose to plot at each redshift the SDSS band closest to the rest frame of the ACS filter (z ≥ 1: u band, plus signs; 0.5 ≤ z ≤ 0.9: g band, crosses; z ≤ 0.45: r band, circles). [See the electronic edition of the Supplement for a color version of this figure.]
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