COLOR GRADIENTS AND SURFACE BRIGHTNESS PROFILES OF GALAXIES IN THE HUBBLE DEEP FIELD-NORTH

PIMOL MOTH1 AND RICHARD J. ELSTON2

Department of Astronomy, 211 Bryant Space Science Center, P.O. Box 112055, University of Florida, Gainesville, FL 32611

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ABSTRACT

We fit elliptical isophotes to the Hubble Deep Field North WFPC-2 and NICMOS data to study the rest-frame (UV128−U100) color profiles and rest-frame B surface brightness profiles of 33 intermediate-redshift galaxies (0.5 ≤ z ≤ 1.2) with H414 < 25 and 50 high-redshift galaxies (2.0 ≤ z ≤ 3.5) with H160 < 27. From the weighted least-squares fit to the color profiles we find that at intermediate redshifts the galaxies possess negative color gradients \(\frac{\Delta (UV128−U100)}{\Delta \log r} = -0.091 \pm 0.007 \text{ mag dex}^{-1}\), indicating a reddening toward the center of the profile similar to local samples, whereas at high redshifts the galaxies possess positive color gradients \(\frac{\Delta (UV128−U100)}{\Delta \log r} = 0.272 \pm 0.007 \text{ mag dex}^{-1}\), indicating that star formation is more centrally concentrated. Although the presence of dust can cause some reddening to occur toward the centers of the profiles seen at intermediate redshifts, it cannot explain the strong central blueing of light seen at high redshifts. Thus, we are witnessing a population of galaxies with strong positive color gradients at high redshifts that do not seem to exist in large numbers at lower redshifts. This indicates that star formation is more centrally concentrated in the distant galaxy sample, which differs from the prevalent mode of extended disk star formation that we observe in the local universe. Additionally, we find that it is critical to correct for point-spread function (PSF) effects when evaluating the surface brightness profiles since at small scale lengths and faint magnitudes, an \(r^{1/4}\) profile can be smoothed out substantially to become consistent with an exponential profile. After correcting for PSF effects, we find that at higher look-back time, the fraction of galaxies possessing exponential profiles have slightly decreased while the fraction of galaxies possessing \(r^{1/4}\) profiles have slightly increased. Our results also suggest a statistically insignificant increase in the fraction of peculiar or irregular galaxies. We compare our results with recent semianalytical models that treat galaxy formation and evolution following the cold dark matter hierarchical framework.

Key words: cosmology: observations — cosmology: theory — galaxies: evolution — galaxies: high-redshift — galaxies: starburst

1. INTRODUCTION

Two of the most fundamental and intriguing questions in astronomy are how galaxies form and how they evolve with time. To answer these questions, we must be able to compare and contrast the properties of galaxies at different redshifts. Whereas we have a wealth of information about galaxies at z ≤ 1.0, our knowledge of the properties of galaxies at higher redshifts is limited. However, with the advent of the Hubble Deep Field North (HDF-N) project (Williams et al. 1996; Thompson et al. 1999; Dickinson 1999; Dickinson et al. 2000), we can probe to fainter surface brightness limits and smaller angular scales than before the sizes, shapes, and colors of distant galaxies that will ultimately yield important clues to understanding their structure, formation, and subsequent evolution. The near-infrared data from NICMOS combined with the optical data from the Wide Field Planetary Camera 2 (WFPC-2) give us the unique opportunity to compare the surface brightness properties of galaxies at the same rest-frame wavelengths over a range of redshifts, allowing us to better understand galaxy formation and evolution from an observational standpoint.

One observational test of galaxy evolution is the study of color profiles that will give us an idea of the distribution of stellar populations in the galaxies and whether this distribution changes with time. Because of limits in resolution, the study of the color profiles of galaxies has been predominantly restricted to the low- and intermediate-redshift regimes. However, the deep, high-resolution, multiwavelength data from the HDF-N probed in this study provide us with the rare opportunity to study the color profiles of galaxies at higher redshifts than those studied in the past. Previous studies of early-type galaxies at z ≤ 1.0 have shown that they tend to have redder colors in their central regions and gradually become bluer outward (Tamura et al. 2000; Tamura & Ohta 2000; Vader et al. 1988; Franx, Illingworth, & Heckman 1989; Peletier, Valentijn, & Jameson 1990). This trend in the color profiles can be explained by either a stellar age or metallicity gradient that becomes degenerate at z = 0 (Silva & Elston 1994). Most studies concur that models involving the metallicity gradient best reproduce the color gradients seen in early-type galaxies at z ≤ 1.0. On the other hand, the gradients observed in late-type galaxies may be due to both age and metallicity effects; i.e., the central parts of the galaxies in general have older stars and higher metallicity than the outer parts, making them have redder colors toward the centers. In the study of the near-IR and optical color profiles of 86 face-on disk-dominated galaxies, de Jong (1996) concluded that their color gradients were best reproduced by models involving both stellar age and metallicity gradients. The existence or lack of dust in galaxies can also complicate matters and must be addressed when interpreting color profiles since, in theory, dust may also be responsible for the central redden-
ing in galaxies if we assume that dust generally tends to be more concentrated in the center and consequently would produce more extinction there (de Jong 1996; Evans 1994; Byun, Freeman, & Kylafis 1994).

A study of the color profiles and surface brightness profiles of galaxies spanning a wide range of redshifts will help us place constraints on galaxy formation and evolution by enabling us to compare what we learn from observations with what we predict from theoretical models. Currently, the hierarchical structure formation model (Baugh et al. 1998, hereafter BCFL; Cole et al. 1994; Kauffmann, Nusser, & Steinmetz 1997; Roukema et al. 1997; White & Frenk 1991) represents the popular framework for how structure formed and evolved in the universe. This model assumes that the universe is dominated by nonbaryonic dark matter that interacts with visible matter only through its gravitational influence and ultimately determines where galaxies will form. It predicts that the gravitational perturbations in the early universe will cause the smallest mass fluctuations to collapse first and then to subsequently merge into progressively larger structures until they form the mature galaxies we observe today. BCFL analyzed the properties of the high-redshift Lyman break galaxies in the context of this model. In their semianalytical treatment of galaxy formation in hierarchical clustering theories, they generated mock catalogs of the high-redshift Lyman break galaxies (LBGs) by using the color criterion imposed by Steidel & Hamilton (1993) and modeled the growth of dark matter haloes by the accretion of matter through mergers, taking into account the cooling of gas into stars and feedback. Somerville, Primack, & Faber (2001, hereafter SPF) also applied semianalytical models of galaxy formation within the hierarchical clustering framework to analyze the population of Lyman break galaxies at high redshift. Since they conveniently address the properties of Lyman break galaxies (the sample of significant interest to us) within the current popular framework for galaxy formation and evolution, we will interpret our results within the context of the BCFL and SPF models.

2. DATA AND SAMPLE SELECTION

It is important to study the properties of the galaxies at different redshifts at the same rest-frame wavelengths because some galaxies might experience what are called "morphological k-corrections." This is a phenomenon that occurs when galaxies at different redshifts look different when viewed through the same passband since the passband would represent different rest-frame wavelengths. For example, the F606W image for a galaxy at redshift \( z = 0.5 \) would reflect the properties of the galaxy at the rest optical wavelengths whose light would include both young and old stellar populations, whereas for a galaxy at redshift \( z = 3 \), the F606W image would represent the rest-UV wavelengths of the galaxy, which is dominated by the younger, bluer stellar populations. Thus, if we want to compare the properties of the same stellar populations, we need to choose our passbands such that they reflect the same rest wavelengths at all redshifts.

The original HDF-N data were a Director’s Discretionary program on the Hubble Space Telescope designed to image a field at high galactic latitude by using the WFPC-2 camera in four passbands spanning the wavelengths 0.3–0.8 \( \mu m \) (Williams et al. 1996). At low redshifts, these images were sufficient to study the galaxies in the rest-frame optical wavelengths; however at \( z > 1 \), the WFPC-2 images could be used only to study the rest ultraviolet properties of the galaxies since their rest optical wavelengths were shifted into the near-IR. Near-IR data of galaxies in the HDF-N were available from ground-based observations (Dickinson et al. 2000; Hogg et al. 1997). However, since the ground-based data were taken at much lower resolution (~1") and reached shallower depths than did the WFPC-2 images, it was very difficult to compare the properties of high-redshift galaxies with their lower redshift counterparts at the same rest-frame wavelengths. To address this problem, Dickinson et al. (2000), embarked on a General Observer’s (GO) Program 7817 to image the entire WFPC-2 region of the HDF-N in the near-IR by using the NICMOS Camera 3 F110W and F160W filters. The data reached an average depth of \( AB = 26.1 \) in F110W and F160W with a signal-to-noise ratio of 10 in \( 0.7 \) diameter aperture and have a point-spread function (PSF) of FWHM = 0.22 after the dithered data were combined by drizzling. To avoid the morphological k-correction problem, we study the intermediate-redshift galaxies in the HDF-N by using the WFPC-2 images taken in F450W (\( B_{450} \)), F606W (\( V_{606} \)) and F814W (\( I_{814} \)) and the high-redshift galaxies by using WFPC-2 F814W (\( I_{814} \)) and the NICMOS CAM3 images taken in F110W (\( I_{110} \)) and F160W (\( H_{160} \)) to probe their rest-frame near-UV and optical properties.

Since we will be comparing the color profiles of galaxies at a range of redshifts, it is important to establish what we mean by intermediate- and high-redshift galaxies. We define intermediate-redshift galaxies as those having redshifts in the range \( 0.5 \leq z \leq 1.2 \), and high-redshift galaxies as those having redshifts in the range \( 2.0 \leq z \leq 3.5 \). We do not include galaxies with \( 1.2 \leq z \leq 2.0 \) in our sample because at these redshifts there are no prominent optical features to constrain the redshifts with the high precision required in our study. Our sample consists of 33 intermediate-redshift galaxies with \( I_{814} < 25 \) identified by spectroscopic redshifts (Cohen et al. 1996; Zepf, Moustakas, & Davis 1997) and 50 high-redshift galaxies with \( H_{160} < 27 \), of which 25 were identified by spectroscopic redshifts (Steidel et al. 1996; Lowenthal et al. 1997) and 25 by photometric redshifts (Budavári et al. 2000). In our paper, we assume a cosmology where \( H_0 = 71 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0.3 \).

3. METHODOLOGY

3.1. Surface Photometry

We performed detailed surface photometry on our sample of galaxies by using the ELLIPSE task in the IRAF/STSDAS package. This task fits elliptical isophotes to the galaxies by using the iterative scheme described in Jedrzejewski (1987). We entered initial guesses for the ellipse center \( (x, y) \), ellipticity \( \epsilon \), and position angle \( \phi \) and allowed the task to update these parameters following the iteration scheme. The errors in the azimuthally averaged intensity are obtained from the rms scatter of the intensity measurements along each fitted isophote. To generate color profiles, it was important that we kept the ellipses fixed between the different filters since positional displacement of the isophotes in the different filters may cause the color distribution of the galaxy to be artificially asymmetric. Thus, we combined the images taken in different passbands, fitted ellipses to the
combined image, and then used the set of ellipses generated from the combined image as the input ellipses for no-fit mode on each individual image. In this way, we made sure that the surface brightness profiles from the different bands were generated using the same fitted ellipses. It is also important that the PSFs between the different filters match. This was accomplished by degrading the $B_{450}$, $V_{606}$, $I_{814}$, and $J_{110}$ images to match the resolution of the $H_{160}$ image. The PSF matching was verified by looking for color gradients in stellar profiles. Many of the galaxies, especially at high redshifts, possessed nearby companions. To perform the fits only on the galaxy of interest, we masked out the companion. We then converted all fluxes to AB magnitudes.

3.2. Fitting Surface Brightness Profiles

From the elliptical isophotes, we produced azimuthally averaged radial surface brightness profiles. For our intermediate-redshift sample, we produced surface brightness profiles of the images taken in $I_{814}$, while for the high-redshift sample, we produced surface brightness profiles for the images taken in $H_{160}$. At the respective redshifts of the galaxies, these images represent approximately their rest-frame $B$ wavelengths.

We analyzed the resulting intensity distribution by using the STSDAS task NFTIT1D to perform $\chi^2$ fitting to the surface brightness profiles. Normally we would fit the profiles with the sum of an $r^{1/4}$ bulge (de Vaucouleurs 1948) and an exponential disk (Freeman 1970) profile. However, for most of the galaxies, especially at high redshifts, the scale lengths of the galaxies were so small and severely affected by PSF smearing that it was difficult to obtain reliable fits by using these profiles. Thus, we decided to fit the radial light profiles with a generalized exponential,

$$S(r) = S(e) \exp\left\{-1.9992n - 0.3271\right\} |r/R(e)^{1/n} - 1| ,$$

where $R(e)$ is the half-light radius, $S(e)$ is the flux at $R(e)$, $S(r)$ is the surface brightness at $r$, and $n$ is the Sérsic index, which tells us about the degree of flattening in the profile (Sérsic 1968; $n = 1$ recovers the exponential disk profile, and $n = 4$ recovers the $r^{1/4}$ law). Trujillo et al. (2001) have applied an analytical approach to study the effects of the PSF on the Sérsic profiles. They found that, of the free parameters in the Sérsic profile, the one that is affected most by the PSF is $n$, which is smaller in the observed profile than in the actual profile. Furthermore, the higher the original value of $n$ is, the more it will be affected by the PSF. At the faint magnitudes and small scale lengths of typical high-redshift galaxies in the HDF-N, we will all have the PSF on the Sérsic profile with $n < 1$. It then becomes challenging to distinguish between galaxies having exponential profiles from those having de Vaucouleurs profiles. The next section explains our attempts to understand the effects of the PSF on the surface brightness profiles to more accurately classify morphologies.

3.3. Creating Model Galaxies to Account for PSF Effects

To account for the effects of the PSF on the data, we created model galaxies and convolved them with the PSF to match the resolution of the data. To reproduce the surface brightness profiles of the intermediate-redshift sample, we created 10 galaxies with exponential disk profiles ($n = 1$) and 10 with $r^{1/4}$ ($n = 4$) bulge profiles with varying half-light radii and $I_{814}$ magnitudes 21, 22, 23, and 24 (this spans the range of magnitudes in our intermediate-redshift sample) for a total of 80 galaxies. Since the WFPC-2 and NICMOS images have all been degraded to match the resolution of the $H_{160}$ passband, we convolved the model galaxies with an isolated, unsaturated star taken from this passband. We performed the convolution using the IRAF task FCONVOLVE, which takes the Fourier transform of the model galaxy and the PSF (normalized to conserve flux), multiplies them together, and then takes the inverse transform of the product to produce the final convolved galaxy. We then added the model galaxies onto blank areas of the sky in the HDF $I_{814}$ image. By doing so, we include the contribution of the background noise in the image. However, we have chosen to neglect the Poisson noise from the galaxies themselves since it is negligible compared with the background noise. To simulate our high-redshift sample, we repeated the process but added the model galaxies onto blank areas of the HDF $H_{160}$ image with $H_{160}$ magnitudes 23 and 24.

We then generated surface brightness profiles and fitted Sérsic profiles to the convolved disk and spheroid galaxies to determine the degree of flattening due to the PSF. Tables 1 and 2 lists the half-light radii and the Sérsic indices of the convolved model galaxies with a range of magnitudes in the $I_{814}$ and $H_{160}$ passbands, respectively. From Tables 1 and 2, we can see that after convolution with the PSF the profiles of all the galaxies are significantly flattened; i.e., their Sérsic index $n$ decreased significantly from the original profile (recall that $n = 1$ for disks and $n = 4$ for spheroids). In fact, Table 1 shows that after convolution with the PSF, the Sérsic indices of the mock intermediate-redshift galaxies originally possessing an $r^{1/4}$ profile can drop all the way to a value of 1, indicative of an exponential profile. Table 2 shows an even more drastic drop in Sérsic indices of the mock high-redshift galaxies after they had been convolved with the PSF of the HDF. At these small scale lengths and faint magnitudes, typical of the high-redshift galaxies in our sample, the Sérsic indices of the model spheroids drop to 1 and below, rendering them almost indistinguishable from the model disks. Furthermore, the smaller the galaxy is, the more the value of $n$ decreases for both the disk and bulge models. Consequently it would be very difficult to determine from the convolved profile whether it originally possessed an exponential or an $r^{1/4}$ profile.

Fortunately, trends exist that allow us to reliably distinguish between the two types of galaxies even after they have been significantly flattened by the PSF. We note that at a given radius and magnitude both profiles are severely smoothed out, but that $n$ for the spheroid is always higher than $n$ for the disk; i.e., the disk has a more flattened profile. For example, at $I_{814} = 21$ and half-light radius approximately $0''84$, $n$ for the spheroid is 1.736, whereas $n$ for the disk it is 0.789 (Table 1), which is significantly lower. This trend occurs at all radii and magnitudes. Thus, although the surface brightness profiles of the galaxies in the HDF-N are significantly affected by the PSF, we can still broadly classify galaxies morphologically by comparing the value of $n$ and the half-light radii of these galaxies at a given magnitude with those of our model galaxies. However, caution must be taken when using this method to classify the morphologies of galaxies with half-light radii less than $0''12$ since it would be pushing the resolution limit of the instrument and, conse-
TABLE 1
HALF-LIGHT RADI AND SÉRISIC INDICES OF CONVOLVED MODEL DISKS (n = 1) AND SPHEROIDS (n = 4) IN THE I_n Band

| ID | Profile  | R_23^a | n_23^b | R_23^c | n_23,d | R_33^e | n_33^f | R_33,g | n_33,h |
|----|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| Gal 1 | Disk | 1.012 | 0.781 | 0.984 | 0.790 | 0.928 | 0.771 | 0.840 | 0.805 |
| Gal 2 | Disk | 0.956 | 0.816 | 0.956 | 0.800 | 1.024 | 0.789 | 0.900 | 0.630 |
| Gal 3 | Disk | 0.844 | 0.789 | 0.816 | 0.750 | 0.772 | 0.689 | 0.696 | 0.582 |
| Gal 4 | Disk | 0.800 | 0.793 | 0.800 | 0.769 | 0.836 | 0.746 | 0.768 | 0.676 |
| Gal 5 | Disk | 0.712 | 0.785 | 0.712 | 0.765 | 0.756 | 0.747 | 0.720 | 0.732 |
| Gal 6 | Disk | 0.628 | 0.773 | 0.628 | 0.744 | 0.596 | 0.714 | 0.600 | 0.681 |
| Gal 7 | Disk | 0.556 | 0.740 | 0.552 | 0.713 | 0.536 | 0.690 | 0.508 | 0.690 |
| Gal 8 | Disk | 0.480 | 0.727 | 0.472 | 0.696 | 0.460 | 0.671 | 0.440 | 0.643 |
| Gal 9 | Disk | 0.408 | 0.692 | 0.400 | 0.678 | 0.392 | 0.655 | 0.380 | 0.631 |
| Gal 10 | Disk | 0.308 | 0.707 | 0.304 | 0.694 | 0.300 | 0.668 | 0.296 | 0.630 |
| Gal 11 | Disk | 0.292 | 0.595 | 0.300 | 0.591 | 0.274 | 0.570 | 0.240 | 0.540 |
| Gal 12 | Spheroid | 0.804 | 1.651 | 0.764 | 1.366 | 0.704 | 1.094 | 0.604 | 0.910 |
| Gal 13 | Spheroid | 0.748 | 1.403 | 0.692 | 1.336 | 0.596 | 1.127 | 0.624 | 0.987 |
| Gal 14 | Spheroid | 0.704 | 1.572 | 0.656 | 1.360 | 0.596 | 1.151 | 0.440 | 0.910 |
| Gal 15 | Spheroid | 0.604 | 1.521 | 0.560 | 1.337 | 0.496 | 1.111 | 0.432 | 0.906 |
| Gal 16 | Spheroid | 0.564 | 1.517 | 0.548 | 1.346 | 0.508 | 1.115 | 0.452 | 0.914 |
| Gal 17 | Spheroid | 0.508 | 1.480 | 0.504 | 1.325 | 0.492 | 1.114 | 0.456 | 0.913 |
| Gal 18 | Spheroid | 0.436 | 1.368 | 0.428 | 1.266 | 0.384 | 1.089 | 0.352 | 0.917 |
| Gal 19 | Spheroid | 0.388 | 1.320 | 0.392 | 1.227 | 0.388 | 1.108 | 0.400 | 0.984 |
| Gal 20 | Spheroid | 0.300 | 1.088 | 0.300 | 1.063 | 0.296 | 0.992 | 0.304 | 0.870 |

TABLE 2
HALF-LIGHT RADI AND SÉRISIC INDICES OF CONVOLVED MODEL DISKS (n = 1) AND SPHEROIDS (n = 4) IN THE H Band

| ID | Profile  | R_23^a | n_23^b | R_23^c | n_23,d | R_33^e | n_33^f | R_33,g | n_33,h |
|----|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| Gal 1 | Disk | 0.488 | 0.754 | 0.288 | 0.605 |
| Gal 2 | Disk | 0.432 | 0.672 | 0.384 | 0.623 |
| Gal 3 | Disk | 0.372 | 0.635 | 0.364 | 0.630 |
| Gal 4 | Disk | 0.292 | 0.595 | 0.300 | 0.591 |
| Gal 5 | Disk | 0.252 | 0.593 | 0.248 | 0.582 |
| Gal 6 | Disk | 0.232 | 0.590 | 0.228 | 0.554 |
| Gal 7 | Disk | 0.232 | 0.622 | 0.236 | 0.588 |
| Gal 8 | Disk | 0.220 | 0.618 | 0.208 | 0.599 |
| Gal 9 | Disk | 0.200 | 0.615 | 0.208 | 0.609 |
| Gal 10 | Disk | 0.188 | 0.622 | 0.196 | 0.592 |
| Gal 11 | Spheroid | 0.416 | 0.848 | 0.356 | 0.716 |
| Gal 12 | Spheroid | 0.392 | 0.892 | 0.368 | 0.804 |
| Gal 13 | Spheroid | 0.364 | 0.904 | 0.332 | 0.771 |
| Gal 14 | Spheroid | 0.296 | 0.794 | 0.304 | 0.783 |
| Gal 15 | Spheroid | 0.272 | 0.785 | 0.260 | 0.715 |
| Gal 16 | Spheroid | 0.248 | 0.760 | 0.240 | 0.731 |
| Gal 17 | Spheroid | 0.240 | 0.744 | 0.236 | 0.690 |
| Gal 18 | Spheroid | 0.224 | 0.715 | 0.240 | 0.686 |
| Gal 19 | Spheroid | 0.208 | 0.690 | 0.196 | 0.636 |
| Gal 20 | Spheroid | 0.204 | 0.687 | 0.212 | 0.681 |

a Half-light radii in arcseconds for I_n = 21.
b Sérisic index for I_n = 21.
c Half-light radii in arcseconds for I_n = 22.
d Sérisic index for I_n = 22.
e Half-light radii in arcseconds for I_n = 23.
f Sérisic index for I_n = 23.
g Half-light radii in arcseconds for I_n = 24.
h Sérisic index for I_n = 24.

3.4. Generating Color Profiles and Determining the Gradients

We determined the color profiles of the galaxies by subtracting the surface brightness profile of one passband from the surface brightness profile of the adjacent passband. For our intermediate-redshift sample we generated B_1400–V_1060 color profiles, and for our high-redshift samples we produced I_n–J_110 color profiles. We then applied the k-corrections described in the following section to transform them to their rest-frame (UV_128–U_3000) colors, where UV ~ 2192 Å and U ~ 2943 Å. The k-corrections are minimal since we have chosen to work with passbands that closely map to their rest-frame wavelengths. We then performed a weighted least-squares fit to the profile. We started the fit 0."14 out from the center of the profile since the color differences near the center might reflect slight differences in the PSF between the two passbands rather than indicate true color changes in the galaxy. From the fits, we were able to obtain the value of the color gradient.
\[ \Delta(UV_{218} - U_{300})_0 / \Delta \log r_f \text{, where } (UV_{218} - U_{300})_0 \text{ is the rest-frame color and } r_f \text{ is the radius in kiloparsecs. The main source of error in this procedure is the uncertainty in the determination of the local sky background values. The global sky background subtraction might be adequate for the larger and brighter galaxies in our intermediate-redshift sample, but for the smaller and fainter galaxies in our high-redshift sample there could be residuals in the background that could significantly change the value and even the sign of the color gradient if the effect is huge. We determined the value of the local sky background by extending the elliptical isophotes out past 5 scale lengths in 0.12 increments, taking care to mask out nearby objects. We then adopted the value of our background as the typical value of the isophotes located far enough from the object such that the flux level ceased to decrease steadily, but instead it fluctuated around some value. From this method, we found that in general there had been an overestimation in the global background value in the reduced images used for this study.} 

3.5. \(k\)-Corrections

When we observe two galaxies at different distances with the same intrinsic brightness through the same passband, we measure two different magnitudes, not only because of the inverse square law but also because their spectral energy distributions (SEDs) will be shifted toward longer wavelengths and also “stretched” by a factor of \(1 + z\) because of the expansion of the universe. To correct for this effect and to convert the color profiles to their rest-frame values, we need to apply \(k\)-corrections to our results. We use the definition of the \(k\)-correction from Oke & Sandage (1968),

\[
K_i(z) = 2.5 \log(1 + z) + 2.5 \log \frac{\int S_i(\lambda) F(\lambda) d(\lambda)}{\int S_i(\lambda) F(\lambda/(1 + z)) d(\lambda)},
\]

where \(S_i(\lambda)\) is the sensitivity function of the detector \(i\), \(F(\lambda)\) is the observed energy flux density, \(F(\lambda/(1 + z))\) is the energy flux density of the galaxy at rest, \(d(\lambda)\) is the bandwidth of the detector \(i\), and \(K_i(z)\) is the \(k\)-correction of the galaxy observed through detector \(i\) at redshift \(z\). The first term of the correction is due to the “stretching” of the passband whereas the second term represents the shifting of the SED to longer wavelengths.

Since \(k\)-corrections do not currently exist for the NIC-MOS passbands, we generated our own set by using the SEDs from Devriendt, Guiderdoni, & Sadat (1999). They used the STARDUST model to produce SEDs for 17 galaxies ranging from local spirals, starbursts, luminous infrared red galaxies, and ultraluminous infrared galaxies extending from the far-UV to submillimeter wavelengths. Their SEDs also included the effects of internal extinction and emission of dust in the galaxies.

4. SURFACE BRIGHTNESS PROFILES

In the process of analyzing the color profiles of the galaxies, we also studied their surface brightness profiles. Tables 3 and 4 list the statistics for the 33 galaxies in the intermediate-redshift and 50 galaxies in the high-redshift regime, respectively. Column (4) of Tables 3 and 4 lists the Sérsic indices in the \(I_{814}\) passband for galaxies at intermediate redshifts and the \(H_{160}\) passband for galaxies at high redshifts. These passbands translate to approximately the rest-frame \(B\) band for all the galaxies. Ideally galaxies that possess exponential profiles would have a Sérsic index of 1 whereas galaxies that possess a de Vaucouleurs profile would have a Sérsic index of 4. Thus, from a naive inspection of the Sérsic indices of the galaxies at high redshifts, we would assume that only one (ID 4-555.11 with \(n = 1.467\)) has a steeper profile than an exponential. However, we have demonstrated in § 3.3 that when we classify morphologies based on the Sérsic indices, it is critical to take into account the role of the PSF since in many cases, especially at high redshifts, the PSF can smooth what was originally an \(r\)-profile to one with \(n < 1\). Column (5) lists our profile classification for each galaxy (after taking into account PSF effects), based on the galaxy models discussed in § 3.3, where “deV” represents a de Vaucouleurs \(r^{1/4}\) profile, “Exp” represents an exponential profile, “Int” represents an intermediate profile with \(1 < n < 4\) (these galaxies most likely possess both a bulge and disk component), and “O” represents “others” for galaxies showing irregular structure that could not be fitted with any profile. In our attempt to classify the morphologies of the galaxies, we do not automatically assume that objects that possess exponential profiles are disks while objects that possess de Vaucouleurs profiles are spheroids since this is not necessarily always the case because many dwarf spheroids have been shown to possess exponential profiles (Koo et al. 1994, 1995). We naively lump into one category (“O”) those galaxies that have irregular profiles and do not follow an exponential or \(r^{1/4}\) law. Wu (1999) explains that there are actually two types of “irregular” galaxies. One type is the traditional irregular, which is the late-type system classified in the Hubble scheme, whereas the other type possesses an irregular profile as a result of galaxy-galaxy interactions and mergers. However, it is not within the scope of this paper to differentiate between the two types. Thus, it is evident that our classification scheme represents an oversimplification designed to obtain a sense of the overall trends in the morphologies of the galaxies and should not be taken as a robust classification scheme on the individual level.

Figures 1–3 show the surface brightness profiles and the fits to the profiles of all the galaxies in our sample. The Williams et al. (1996) identification numbers and Sérsic indices are included in the plots. Figures 4 and 5 represent plots of the half-light radii versus the Sérsic indices \((r_{1/2} - n)\) of the model disks and spheroids after they had been convolved with the HDF PSF in the \(I_{814}\) (with \(I_{814} = 21, 22, 23, \) and 24) and \(H_{160}\) (with \(H_{160} = 23 \) and 24) passband, respectively. Again, for the high-redshift sample, the results from the galaxy models are reliable only for \(H_{160} \geq 24.5\) since for fainter magnitudes it is difficult to clearly distinguish the locus of Sérsic indices for the model spheroids from the locus of Sérsic indices for the model disks. The triangles represent the values for the model spheroids and the asterisks represent the values for the model disks. The dashed and dotted lines represent weighted least-squares fit to the model spheroids and model disks, respectively, whereas the solid lines represent the 1 \(\sigma\) error in the fits. For all \(I_{814}\) magnitudes and for \(H_{160} \leq 24.5\), we have also plotted the values of the galaxies in our intermediate- and high-redshift sample (squares) to attempt to classify their morphologies by observing where they fall on the diagram. We do not include in these plots those galaxies that could not be fitted by the Sérsic law since their profiles were too irregular. These galaxies, however,
were still included in our statistics and were labeled “O” for “others.” At intermediate redshifts, the morphologies are better constrained since the galaxies are brighter and the distinction between the model spheroids and disks is more apparent. As a further check on the accuracy of our classification system, we can utilize the images we have of the intermediate-redshift galaxies since for many they are large enough and bright enough to classify their morphologies by eye.

With the $r_{1/2} - n$ plots, we have attempted to classify the morphologies of all the galaxies in the intermediate-redshift bin and those with $H_I < 24.5$ in the high-redshift bin, although it should be kept in mind that the process is rather crude since it relies mainly on the galaxy models, which should be regarded as highly speculative at small scale lengths and faint magnitudes. The galaxies whose Sérsic indices fall above the locus for the model spheroids were classified as possessing $r^{1/4}$ profiles since this would indicate that they possess profiles that are steeper than our models, whereas those whose Sérsic indices fall below the locus for the model disks are classified as possessing exponential profiles since this would indicate they possess profiles that are shallower than our models. For the galaxies that have Sérsic indices in between the locus of our model spheroids and disks, we placed an acceptance limit of $5\sigma$. If the values of the Sérsic indices were less than $5\sigma$ away from the locus of spheroids, we classified them as possessing $r^{1/4}$ profiles; if they were less than $5\sigma$ from the locus of the disks, we classified them as possessing exponential profiles; and if they were more than $5\sigma$ away from either loci, we classified them as possessing intermediate profiles. There were a few galaxies that possessed Sérsic indices with less than $5\sigma$ deviations from both loci. In these cases, we classified them according to the magnitude of their deviation. If the deviation from the locus of model spheroids was less than it was from the locus of model disks, then we classified those galaxies as possessing $r^{1/4}$ profiles. If, however, the converse was true, we classified those galaxies as possessing exponential profiles. But here is where we introduce some uncertainty in our classification scheme. Since these galaxies have such small
deviations from both loci, even though we associate these galaxies with a certain profile, it does not mean that it cannot possess the other types of profiles. For example, ID 3-404 was classified as possessing an exponential profile since its Sérsic index was only 3.3. It does not mean that it cannot possess the other types of profiles. For example, ID 3-404 was classified as possessing an exponential profile since its Sérsic index was only 2.1 \( \sigma \) away from the locus of the model disks; however, there is still a good chance that it could possess an \( r^{1/4} \) profile since it was only 3.3 \( \sigma \) away from the locus of model spheroids. Or it could also possibly possess an intermediate profile. There are only two galaxies in the intermediate-redshift sample (IDs 2-353 and 3-404)
and one in the high-redshift sample (ID 2-321) that have less than 5 \( \sigma \) deviations from both loci. If we include these uncertainties, it will at most increase the Poissonian errors by 1\%. Thus, the profile classification is very robust, and the uncertainties in the classification system is dominated by the Poissonian error.

Table 5 summarizes our best effort to classify the morphologies of the galaxies, based on the combination of the results from the fits to the surface brightness profiles of the galaxies in the two redshift bins, the plots of the galaxy models, and visual inspection. Quoted are the percentages found for each profile with their Poissonian error. The number of galaxies possessing each profile is in parenthesis. In our intermediate-redshift sample, of 32 galaxies we classified 28\% as possessing \( r^{1/4} \) profiles, 53\% as possessing exponential profiles, 13\% as intermediates, and 6\% as “others” since they possessed irregular structure, precluding a fit to the profile.

Table 5 summarizes our best effort to classify the morphologies of the galaxies, based on the combination of the results from the fits to the surface brightness profiles of the galaxies in the two redshift bins, the plots of the galaxy models, and visual inspection. Quoted are the percentages found for each profile with their Poissonian error. The number of galaxies possessing each profile is in parenthesis. In our intermediate-redshift sample, of 32 galaxies we classified 28\% as possessing \( r^{1/4} \) profiles, 53\% as possessing exponential profiles, 13\% as intermediates, and 6\% as “others” since they possessed irregular structure, precluding a fit to the profile.

Table 5

| Redshift  | Total | de Vaucouleurs | Exponentials | Intermediates | Others |
|----------|-------|----------------|--------------|---------------|-------|
| 0.5 \leq z \leq 1.2 \ldots | 32 | 28\% \pm 9\% (19 \pm 3) | 53\% \pm 13\% (17 \pm 4) | 13\% \pm 6\% (4 \pm 2) | 6\% \pm 3\% (2 \pm 1) |
| 2.0 \leq z \leq 3.5 \ldots | 20 | 60\% \pm 15\% (12 \pm 3) | 20\% \pm 10\% (4 \pm 2) | 0\% (0) | 20\% \pm 10\% (4 \pm 2) |

Fig. 1.—\( I_{814} \) surface brightness profiles for our intermediate-redshift sample. The dotted line represents a generalized exponential fit to the profile. Included in the plots are the galaxy ID from the Williams et al. 1996 catalog and the value of the Sérsic index (\( n \)). Those galaxies with no Sérsic index indicated have irregular structure, precluding a fit to the profile.
model disks is very small, there is not a clearly defined region for the intermediate cases.

We must stress that we are limited by small number statistics, especially at high redshifts since we are able only to classify the morphologies of 20 of our original 50 galaxies. Nevertheless, we can still comment on the trends seen. From Table 5, we see that at higher look-back time the fraction of the galaxies possessing $r^{1/4}$ profiles increased by 32% whereas the fraction of exponential-type profiles decreased by 33%. These differences are marginally significant since they represent changes in both cases. Our results differ from what has been previously published (Marleau & Simard 1998). By using a profile decomposition method on 522 galaxies down to $m_{F814W} < 26$, Marleau & Simard (1998) found that the majority of HDF-N galaxies are disk-dominated, with only 8% having dominant bulge fractions. They interpreted their results as measuring a decrease in the number of bulge-dominated galaxies as a function of look-back time. Given the high degree of difficulty in the classification of the morphologies of these small faint galaxies, which are severely affected by the PSF and the limitation of small number statistics, it is not surprising that at this point we are not able to reach a consensus. At high redshifts, we also see a statistically insignificant increase of 14% in the fraction of galaxies that we have classified as “others.” This is along the lines of what was observed in previous studies of galaxies in the HDF-N that have shown that by $I_{AB} > 24$ there are few galaxies possessing traditional Hubble sequence morphologies. Instead they tend to be more “peculiar” in the sense that they may represent mergers in progress (Abraham et al. 1996; Bunker 1999). Although we detect changes in morphology between the two redshift bins, these changes may not be solely attributed to evolution. In § 6 we discuss the possibility that the trends in morphology may be influenced by observational selection effects.

5. COLOR PROFILES

We generated $B_{450}$ and $I_{814}$ color profiles for the 33 intermediate-redshift and 50 high-redshift sample, respectively, and applied $k$-corrections to determine whether these galaxies exhibited significant color changes [i.e., $|\Delta(UV_{218} - U_{300})/\Delta \log r| > 0.2$ mag dex$^{-1}$] in their rest-frame $(UV_{218} - U_{300})$ profiles (Figs. 6–8). We can assume that since we are observing the color profiles for the rest-frame $(UV_{218} - U_{300})$, we will be probing primarily the light from the young stars. Thus, the sign of the gradient will give us an idea of the locations of the star-forming regions if the color gradient is caused by an age gradient alone. If the

![Fig. 2.—Same as Fig. 1, but for $H_{160}$ in the high-redshift sample](image-url)
A galaxy possesses a positive gradient, this would indicate a bluing toward the center, which might be explained by star formation that is centrally concentrated. If the galaxy possesses a negative gradient, this would point to a bluing with increasing radius, which would imply an older stellar population in the center. If, however, we observe no significant gradient in the galaxy, we can assume that the star formation regions are uniformly dispersed throughout the galaxy.

Because of the $(1+z)^4$ falloff in the surface brightness, the color profiles of our high-redshift sample do not extend to the low surface brightness levels of our intermediate-redshift sample. For example, in our high-redshift galaxies, we might reach depths of as much as 28 mag arcsec$^{-2}$, but because of the fall off in surface brightness, this would translate to a depth of only $\sim24.5$ mag arcsec$^{-2}$ in our intermediate-redshift sample. To consistently compare the results for our two redshift bins, we must sample over approximately the same surface brightness range, thus, we must apply a cutoff in surface brightness in our intermediate-redshift sample. Applying a cutoff in the radial range is approximately the same as applying the cutoff in surface brightness. Thus, we have chosen to fit the color profiles of the intermediate-redshift sample out to a radius of only 4 kpc. This radius cutoff represents approximately twice the mean half-light radius of our high-redshift sample, which was determined by summing up all the light within approximately 28 mag arcsec$^{-2}$. Column (8) in Tables 3 and 4 lists the color gradients from the weighted least-squares fit to the color profiles and their associated errors for our intermediate-redshift and high-redshift samples, respectively. The errors quoted include the uncertainties from the fit and a conservative upper limit in the uncertainty from the systematic background subtraction (approximately $\pm 0.037$ mag dex$^{-1}$).

From Table 3, column (8) we note that 12 (36%) of the galaxies in our intermediate-redshift sample possess positive gradients, but only two of them have gradients greater than 0.2 mag dex$^{-1}$, which indicates that they may have a strong central concentration of star formation perhaps indicative of a burst. Although 64% of the galaxies at intermediate redshifts possess negative gradients, only 39% of them possess gradients less than $-0.20$ mag dex$^{-1}$. Furthermore, the mean of the color gradients of all the galaxies at intermediate redshifts is $-0.091 \pm 0.007$ mag dex$^{-1}$, which is relatively shallow. Thus, although the negative color gradients indicate that, in general, the colors of these galaxies are bluer in the outer parts of the galaxies, since the mean of the gradient is not too steep, the color changes are gradual across the galaxies. Column (8) in Table 4 lists the rest-frame $(U'V' - U'300)_{0}$ color gradients and the associated errors for our high-redshift sample, determined using all the
Fig. 4.—Half-light radii vs. Sérsic index ($n$) for the model disks and spheroids after they were convolved with the $H_{160}$ PSF with $I_{814} = 21$, 22, 23, and 24, showing model spheroids (triangles), model disks (asterisks), and the intermediate-redshift galaxies in our sample (squares). The dashed and dotted lines represent a weighted least-squares fit to the model spheroids and model disks, respectively. The solid lines represent the $1 \sigma$ deviations of the fits.

Fig. 5.—Half-light radii versus Sérsic index ($n$) for the model disks and spheroids after they were convolved with the $H_{160}$ PSF with $H_{160} = 23$ and 24, showing model spheroids (triangles), model disks (asterisks), and high-redshift galaxies in our sample (squares). The dashed and dotted lines represent a weighted least-squares fit to the model spheroids and model disks, respectively. The solid lines represent the $1 \sigma$ deviations of the fits.
isophotes that reach depths as much as \( \sim 28 \) mag arcsec\(^{-2}\).

We note that the color gradients of the majority of the high-redshift galaxies (72\%) are positive with a mean of \( 0.272 \pm 0.007 \) mag dex\(^{-1}\). Of the 36 galaxies that have positive gradients, 83\% have gradients greater than 0.200 mag dex\(^{-1}\), indicating that there are significant color changes across these galaxies.

Figure 9 represents a plot of the redshift versus the color gradients of the galaxies in our two redshift bins. When we compare the rest-frame \((U' - Y)\) color gradients for our intermediate-redshift sample with our high-redshift sample, we detect different trends in the two redshift bins. In our intermediate-redshift sample, we saw a slight trend for a blueing with increasing radius (negative color gradients), implying that the star formation regions may be located generally in the outer disks of the galaxies or that the older stellar populations may be located toward the center. But given that the amplitude of the gradients was not too significant, we conclude that in general the color changes are gradual across the galaxies. However, in our high-redshift sample, the majority of the galaxies possessed significant positive gradients in their color profiles. On average, these color gradients were \( 0.363 \pm 0.010 \) mag dex\(^{-1}\) higher than their lower redshift counterparts. If these color gradients are due primarily to an age gradient, this would mean that these galaxies have bluer colors toward the center, implying that their star formation regions may be centrally concentrated; i.e., there are more young stars at the centers than in the outer parts of the galaxies. Numerous analysis show that both present-day disks and spheroids have metallicity gradients with higher metallicities toward the galaxy centers. Such a metal gradient would only strengthen the age gradient needed to make the centers bluer. Thus, from our analysis, we conclude that there is evolution in the color profiles of galaxies in the HDF-N. When we look further back in time, the star formation regions of the galaxies are more centrally concentrated. Since it is beyond the scope of this paper to generate models to interpret our results, in the next section we discuss modeling of color gradients taken from the literature to infer the dominant processes responsible for producing the trends seen in the color gradients.

### 5.1. Discussion

Not much is currently known about the ultraviolet color gradients of galaxies in the local universe. The few studies of this kind were conducted using the information from the images taken with the Ultraviolet Imaging Telescope during...
the Astro-1 and 2 missions (O'Connell et al. 1992; Ohl et al. 1998). From the Astro-1 mission O'Connell et al. (1992) analyzed the 152-249 color profiles of two Sb bulges and two E galaxies that were generated using the images taken with the 152 and 249 nm filters. They concluded that all but M32 exhibited prominent positive gradients in their profiles. In their study of the FUV (1500 Å) B color profiles for eight early-type galaxies, Ohl et al. (1998) found, again, that all but M32 exhibited large positive color gradients, with differences in color greater than 1.0 mag over the entire profile. These large ultraviolet color gradients are reflective of the “UV upturn” or “UVX” population that has been observed in the far-UV (1200 Å < λ < 2000 Å) imaging of local spiral bulges and early-type galaxies (Code & Welch 1979; de Boer 1982). They propose that a combination of an increase in metallicity combined with the existence of older stellar populations may contribute to producing these color gradients. The trends in the far-UV color gradients of these galaxies are in the opposite sense to what we observe in the rest-frame near-UV for the majority of the intermediate-redshift galaxies in our HDF-N sample and local galaxies that have been observed in the optical and near-IR. However, since the study of the far-UV color profiles of galaxies was conducted at shorter wavelengths and given that the sample sizes were much smaller and limited to only early-type systems and spiral bulges, it is difficult to compare it with our study. Thus, more observations of local galaxies in the ultraviolet are needed to fairly compare with our sample of galaxies at intermediate and high redshifts.

In our intermediate-redshift sample of galaxies, we find that most of the galaxies (six of nine) that we classified as having $r^{1/4}$ profiles possess negative rest-frame $UV'_{218} - U'_{300}$ color gradients, indicating reddening toward the center of the profile. In general, early-type galaxies have been found to exhibit negative gradients; i.e., they have redder colors in the center and gradually become bluer outward (Tamura et al. 2000; Tamura & Ohta 2000; Vader et al. 1988; Franx et al. 1989; Peletier et al. 1990). In their study of the $V_{606} - I_{814}$ color profiles of 10 elliptical galaxies in the HDF-N from $z = 0.1$ to 1.0, Tamura et al. (2000) observed the same trends. They found that all but two (one of them being galaxy 2-251 in our sample) exhibited redder colors toward the centers. At $z = 0$, both an age and a metallicity gradient in the stellar populations can be responsible for producing the negative color gradients observed in the galaxies; i.e., the galaxy colors are redder in the center than in the outer parts because they either have older stellar populations or higher metallicities there. This age-metallicity degeneracy makes it difficult to determine the cause of the color gradient. To break the degeneracy, they generated two model gradients that reproduce the typi-

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**Table**

| $UV'_{218} - U'_{300}$ | $V_{606} - I_{814}$ |
|------------------------|----------------------|
| 2-82                   | 2-239                |
| 2-454                  | 2-449                |
| 2-585.1                | 2-585.1              |
| 2-585.1                | 2-76                 |
| 2-525                  | 2-901                |
| 2-565                  | 2-565                |
| 2-593                  | 2-627                |
| 1-54                   | 2-643                |
| 2-591                  | 4-52                 |
| 3-118                  | 3-243                |
| 4-445                  | 0.3223±0.0439       |
| 0.4189±0.0467          | 0.7873±0.0451        |
| 0.1806±0.0431          | 0.5900±0.0510        |
| 0.3614±0.0413          | 0.1790±0.0450        |
| 0.5355±0.0393          | 0.2922±0.0392        |
| 0.3223±0.0439          | 0.4658±0.0480        |
| 0.0043±0.0400          | 0.0962±0.0373        |
| 1.0336±0.0538          | 0.3748±0.0402        |
| 0.6169±0.0432          | 0.9074±0.0808        |
| 0.0962±0.0373          | 1.0336±0.0538        |
| 0.0651±0.0382          | -0.1846±0.0504       |
| 0.4064±0.0395          | 0.1620±0.0423        |
| 0.3614±0.0413          | -0.0803±0.0536       |

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**Figure 7** — Same as Fig. 6, but for the high-redshift sample
cal color gradients of elliptical galaxies at \( z = 0 \), one caused by a metallicity gradient of old stars, the other from an age gradient of stars with the same metallicity. They then evolved these models to the redshifts of their observed galaxy sample. By comparing the model gradients with the observed gradients, they concluded that the model involving the metallicity gradient agreed well with observations at all redshifts whereas the model involving the age gradient was in good agreement up to a redshift of only \( z < 0.3 \). We also have \( V_{606} - I_{814} \) color profiles for the galaxies in our intermediate-redshift sample that reveal the same trends in the color gradients (Fig. 10). We again observe that over half (five of nine) of the galaxies possessing \( r^{1/4} \) profiles exhibit negative color gradients. Thus, we may interpret the central reddening in the color profiles of the elliptical galaxies in our intermediate-redshift sample in the HDF-N as being primarily due to a metallicity gradient; the centers of the galaxies have higher metallicities than in the outer parts. We observe the same negative trend in the color gradients for the majority of the intermediate-redshift galaxies (14 of 23) that we classified as peculiar or irregular galaxies or as galaxies having exponential profiles. In a study of the near-IR and optical color profiles of 86 face-on disk-dominated galaxies, de Jong (1996) concluded that their negative color gradients were best reproduced by models involving both
stellar age and metallicity gradients. Therefore, we interpret
the gradients seen in the late-type galaxies as arising as a
result of both age and metallicity effects; the central parts of
the galaxies in general have older stars and higher metal-
licity than the outer parts, making them have redder colors
toward the centers.

Whereas the trends seen in the color profiles of our inter-
mediate-redshift sample are well understood, we cannot say
the same for our high-redshift sample. Since this is the first
study of its kind to be conducted on galaxies with \(z \geq 2.0\),
there are no other high-redshift observations of color pro-
files to compare with our results. Thus, we must attempt to
account for the positive gradients seen in our high-redshift
sample by understanding what is responsible for producing
similar trends in the color profiles seen at intermediate and
low redshifts. Guzmán et al. (1998) generated rest-frame
\( B-V \) color profiles for five compact narrow emission line
galaxies (CNELGs), which are low-mass (\( M \leq 10^{10} \, M_\odot \))
starburst systems seen at \( z \leq 1.0 \) and are similar to nearby
\( \text{H} \equiv \) galaxies. They noted that although the gradients were
not significant, there was a slight trend for the bluest color
to occur in the central regions. On average, they found that
the color inside the half-light radius is \( 0.14 \pm 0.05 \) mag bluer
than outside the half-light radius. Guzmán et al. (1998) fur-
thermore describes the CNELGs as having either compact
cores, fans and tails, or several small compact regions.
These morphologies are along the lines of what we see in
our high-redshift sample. They also determined half-light
radii to span from 1 to 5 kpc (\( H_0 = 50 \, \text{km} \, \text{s}^{-1} \, \text{Mpc} \),
\( q_0 = 0.1 \)), which match the range we see in our high-redshift
sample. Given that the morphologies, half-light radii, and
color profiles of the CNELGs are similar to what we observe
in the high-redshift sample, it is not unreasonable to believe
that CNELGs could be the low-redshift, lower luminosity
analogs of the higher redshift Lyman break galaxies. We
can then interpret the positive gradients seen in our high-
redshift sample as being caused by centrally concentrated
starbursts.

The high-redshift galaxies have been shown to possess
modest to high star formation rates (\( 4-25 \, h_{100} \, M_\odot \, \text{yr}^{-1} \),
\( q_0 = 0.5 \); Lowenthal et al. 1997; Steidel, Pettini, & Hamilton
1995; Pettini et al. 1998), which further enforces the idea
that the positive gradients seen in our sample could be
caused by centrally concentrated starbursts. Starbursts can
be triggered by several mechanisms, including mergers and
interactions (Mihos & Hernquist 1994, 1996; Hernquist &
5.2. Sources of Uncertainties

When we discuss the trends seen in the color profiles, we must take into account the uncertainties involved. These uncertainties include the determination of the sky background, the correlation of the pixels, and the role of dust. While statistical errors dominating the inner parts of the color profiles and PSF effects contribute to the uncertainty in the least-squares fit, the systematic errors due to sky subtraction dominate in the outer parts of the profile. To assess how our color gradients are affected by sky subtraction, we chose 20 high-redshift galaxies possessing positive color gradients and for each we obtained statistics on 11 × 11 pixel-wide grids in six blank areas of the sky around the object in the $I_{814}$ and the $J_{110}$ passbands. We generated a histogram of the 726 total pixels in the six grids to determine the mean and the standard deviation of the mean ($\sigma$). For each galaxy, we then determined both a lower and an upper limit of the sky values in $I_{814}$ and $J_{110}$ by subtracting 3 $\sigma$ from the means to obtain their lower limits ($I_{-} - J_{-}$) and adding 3 $\sigma$ to the means to obtain their upper limits ($I_{+} + J_{+}$). Lastly, we generated their $I_{814}-J_{110}$ color profiles and obtained their color gradients for each of the five possible combinations of sky values subtracted off [(1) mean in $I_{814}$ and mean in $J_{110}$, (2) $I_{-} - J_{-}$, (3) $I_{+} + J_{+}$, (4) $I_{-}$ and $J_{+}$, and (5) $I_{+}$ and $J_{-}$]. The means in the color gradients for the five different cases, respectively, are 0.3722, 0.425, 0.321, 0.249, and 0.503, which represent a 3 $\sigma$ deviation of $\sim$0.112 mag dex$^{-1}$, making the typical uncertainty in the estimation of the sky background $\sim$0.037 mag dex$^{-1}$. As we can see, the mean value of the color gradients remains positive and greater than 0.200 mag dex$^{-1}$ in all cases. Thus, we find that the typical gradients seen in the high-redshift galaxies ($\sim$0.26 mag dex$^{-1}$) are significant enough that even with the uncertainties involved in the estimation of the sky background our main conclusion that these galaxies have centrally concentrated star formation still holds.

Another potential source of concern is the correlation of the pixels. Since the images have been drizzled, convolved to recover approximately the same resolution as the $H_{160}$ image, and fitted with ellipses at 0.1 pixel increments, the errors that we obtain from the photometry will be correlated because of the oversampled pixels. Thus, when we performed a weighted least-squares fit to the color profiles, the error bars used in the determination of the weights were correlated. Consequently, the parameters that we obtain from the fit, i.e., the color gradient in this case, may be off from what would be measured if the errors had been independent. To understand how the correlated errors in our photometry affect the least-squares fitting to a straight line, we obtained rms images (M. Dickinson 2001, private communication) in the passbands of interest. These images quantify the uncertainty of the noise in the background (sky + readout noise + dark current) before any processes were performed to cause interpixel correlations. We reanalyzed 10 random galaxies from the intermediate- and high-redshift sample by using the rms images. With the same set of ellipses that we used in the surface photometry, we replaced the correlated errors with the “true” uncorrelated errors for each galaxy. In doing so, we have chosen to neglect the Poisson noise from the galaxies themselves since they are so faint that it would be insignificant compared with the background noise. From this analysis, we find that even after taking into account interpixel correlations, the sign of the color gradients for the galaxies does not change. The high-redshift galaxies still possess predominantly positive color gradients whereas the intermediate-redshift galaxies possess predominantly negative color gradients.

However, the rest-frame ($U_{218}$–$U_{300}$) color profiles may be affected by the presence of dust. In theory, dust can cause the color profiles of galaxies to be redder toward the center if we assume that the dust would be more concentrated at the center and would produce more extinction there (de Jong 1996; Evans 1994; Byun et al. 1994). De Jong (1996) conducted Monte Carlo simulations of light rays traveling through a dusty medium to understand to what extent dust can affect color gradients in late-type systems. They concluded that although a fraction of the color gradients could be attributed to dust, an additional explanation is needed to account for the total reddening in the system. Wise & Silva (1996) produced color profiles extincted by dust for a set of model elliptical galaxies from the $U$ to the $K$ passband and compared them with 52 early-type galaxies from the literature. They concluded that if dust is the primary cause of color gradients then the dust must be spatially extended ($\rho_d \propto r^{-3}$), implying high-dust masses comparable to the dust masses inferred from the IRAS data. Thus, the presence of dust may be partly responsible for producing the color gradients seen in our intermediate-redshift sample for both early-type and late-type systems; however, given that the total mass of the dust and its spatial distribution are not well constrained, we cannot say, for now, to what degree dust affects the color distribution in the galaxies. On the other hand, even though dust might play a role in our high-redshift sample, there is no reason why its presence would cause the color profile to be bluer toward the center. As previously mentioned, dust would tend to cause extinction and, thus, reddening toward the center, not the outer parts of the galaxies. In fact, if dust is found to cause extinction in the centers of these galaxies, then the color gradients seen in our high-redshift sample would be even greater. Thus, although dust may play a role in generating the color gradients of our intermediate-redshift sample, it cannot explain the trends seen in our high-redshift sample.

6. SELECTION EFFECTS

Anytime we compare observations of galaxies in two different redshift ranges, we must take into account the effect of observational selection. At high redshifts, we will be able to detect and study only those galaxies with the highest luminosities and surface brightnesses; thus, the trends that we see in the surface brightness and color profiles may potentially be affected by this bias. We have tried to minimize some selection effects by observing the galaxies at different redshifts in the same rest-frame wavelengths. This guarantees that at all redshifts we will be probing the same...
population of stars. Furthermore, at high redshifts we sample not only galaxies with spectroscopic redshifts, but also galaxies with photometric redshifts that are, in general, fainter than those galaxies that can be detected spectroscopically. Thus, we are sampling the fainter population at high redshifts and are not just picking out the UV luminous galaxies.

Wu (1999) performed simulations on galaxies in the HDF-N to understand the selection effects that may arise when studying galaxies at different redshifts. She takes the galaxies with 0.75 ≤ z ≤ 1.2 in the F814W band and simulates their appearance at z = 1.5 and z = 2.3 by using the corresponding images in F606W and F450W filters, respectively, to minimize k-corrections. She finds that at z = 1.5 only 33% of the original objects can still be detected and by z = 2.3, only 3% of them remain. To further understand the sampling of the galaxy population as a function of redshift, she defines a concentration versus asymmetry index (C20 – C6). She plots the A_W – C_W relation for galaxies in the HDF, separating them into five redshift bins with redshifts ranging from z ≤ 0.6 to redshifts z > 3.0. From these plots, she concludes that whereas the range of A_W and C_W values remain constant for z < 1.2, at higher redshifts the number of high C_W objects seem to decrease while the number of high A_W objects seem to increase. Since high concentration is associated with early-type systems such as elliptical galaxies and early-type spiral galaxies and high asymmetry is associated with merging systems, it seems from her plots that at z > 1.2, there is a decrease in the early-type systems and an increase in merging systems. However, she shows in her work that these trends can naturally be explained by selection effects. In her simulations she has shown that by z = 2.3 most of these galaxies with high concentration have faded so much that they “disappear” into the noise and can no longer be detected.

From Wu’s (1999) discussion it is quite possible that the trends we see in the surface brightness profiles may be influenced by these selection effects. In our work with the surface brightness profiles, if we had not corrected for the PSF effect, we would have seen the same decrease in early-type systems. If we just inspect the Sérsic indices of the galaxies and ignore the effect of PSF smearing, we would naively classify five of a total of 32 (16% ± 7%) of the galaxies in the intermediate sample and only 1 of the 20 (5% ± 5%) galaxies with H ≤ 24.5 in the high-redshift sample as possessing an r^{1/4} profile. Thus, it would seem that the number of early-type systems had decreased with redshift. However, since we have corrected for the effect of the PSF, we recover the number of galaxies with r^{1/4} profiles (i.e., 28% ± 9% for the intermediate-redshift sample, and 60% ± 15% in the high-redshift sample). Thus, by correcting for the PSF, we take care of one selection effect. However, at z > 2, we are still sampling only the tip of the surface brightness function, where asymmetries are more evident. Consequently, it is not surprising that we would find a slightly higher fraction of “irregular” galaxies in the high-redshift sample, 20% ± 10% as opposed to 6% ± 3% in the intermediate-redshift sample. Although the selection effects may be responsible for some of the trends seen in the morphological classification of galaxies, they cannot explain the trends that exist in the color profiles. They cannot explain why at high redshifts we detect a significant population of galaxies possessing large positive color gradients, but at lower redshifts they seem to “disappear.”

7. COMPARISON WITH THEORETICAL MODELS

To fully comprehend galaxy formation and evolution, it is important to compare observations with theoretical models. However, only in the last decade has it been possible to study galaxy formation observationally. Previously, we were able to predict how galaxies form and evolve only by using N-body simulations and semianalytical modeling of dark matter halos, which demonstrated that structure builds up into larger and larger units through continual accretion and merger (BCFL; Cole et al. 1999; Kauffmann et al. 1997; Roukema et al. 1997; White & Frenk 1991). These models gave support to the “hierarchical clustering” scenario pioneered by Peebles (1970), which is a less restricted version of the standard cold dark matter (CDM) model since it allows for the assumption of different cosmologies. In the last several years, much advancement has been made in the observational regime since many have used the Lyman break technique (Steidel & Hamilton 1993) to reliably detect galaxies at high redshift in large numbers. With the detection of numerous high-redshift galaxies at high resolution and sensitivities, it is now feasible to compare observations with theoretical predictions.

From our surface brightness analysis of the galaxies in the HDF-N, we find that as we look further back in time, the star formation regions are more centrally concentrated and their morphologies are more irregular, deviating from the traditional Hubble sequence. Although our results may be affected by uncertainties and selection effects, we can compare with models to test for consistency and determine what may be the driving force behind the trends seen if they are at the very least attributed in some way to galaxy evolution. We have discussed the possibility of mergers and interactions as the cause of the trends seen. To understand how our results fit with the overall picture of galaxy formation and evolution, we compare our observations of galaxies in the HDF-N with the predictions from the semianalytical model of galaxy formation described by BCFL and SPF, which focuses particularly on the high-redshift Lyman break galaxies.

In their model, BCFL used a Monte Carlo simulation to generate binary merger trees, which essentially describe the merging histories for dark matter halos with predetermined final masses. They generated the mock high-redshift progenitors by applying the selection criteria for Lyman break candidates described in Steidel & Hamilton (1993) and quantified the amount of cold gas available by measuring the rate at which cold gas in thin shells can cool to form stars. They chose values for the star formation timescale, the feedback parameter, the shape of the initial mass function, the overall luminosity normalization, and the merger timescale for galaxies that would best reproduce the local B- and K-band luminosity functions. Lastly, they fixed the threshold mass for a galaxy merger causing a disk to become a spheroid to match the relative population of elliptical galaxies, S0s, and spiral galaxies locally. They produced their model for three different cosmologies: the standard CDM model (Ω_0 = 1, h = 0.5, σ_8 = 0.67), the flat CDM model (Ω_0 = 0.3, Λ_0 = 0.7, h = 0.6, σ_8 = 0.97), and the open CDM model (Ω_0 = 0.4, h = 0.6, σ_8 = 0.68).

From their simulations, BCFL show that present-day galaxies that make up the bright end of the luminosity function have at least one Lyman break progenitor at z ~ 3. Furthermore, depending on their merging histories, these Lyman
break progenitors can end up as an $L > L^*$ galaxy with any morphological type. If they experienced major mergers at recent epochs they may evolve to become elliptical galaxies and S0s. If they grew by the quiescent accretion of cooling gas, the gas might form a disk around a bulge that was created by an earlier merger event. And if they experienced minor mergers that were too weak to destroy the disk, they might accumulate more stars in the central bulge. They expect the Lyman break galaxies to be rotating disks with typical half-light radii $\sim 0.5 \ h^{-1} \text{kpc}$ and predict that the stars of the progenitors will congregate primarily in the central regions.

BCFL additionally conclude that the star formation of galaxies at all redshifts occurs quiescently with star formation rates (SFRs) that never obtain a value higher than a few solar masses per year. Their conclusion matches the observations of LBGs only if internal dust extinction is ignored. However, in reality the effect of dust is probably nonnegligible although how much of a role it plays is still presently uncertain. Pettini et al. (1997) measured the extinction to be a factor of $\sim 3$ at $1500 \ \text{Å}$ whereas Meurer et al. (1997) and Sawicki & Yee (1998) report values closer to 15-20. Now the consensus is to use an extinction correction of $\sim 5$ (Meurer, Heckman, & Calzetti 1999; Steidel et al. 1998). If the central blueing seen in the color profiles of our high-redshift sample is caused by a central starburst, which seems likely, then BCFL’s assumption of quiescent star formation in an extended disk does not agree with our observations. On the other hand, the results of the model from SPF would agree well with what we observe in the color profiles and with what we currently know about the SFRs of LBGs. Instead of undergoing quiescent star formation, they favor the idea that LBGs are experiencing what they term “collisional starbursts,” which describe starbursts that are induced by galaxy-galaxy mergers.

SPF explain that they obtain different results from BCFL because of the different assumptions made in the two models. The assumptions made in BCFL for supernovae feedback, gas cooling, and types of mergers were such that taken in combination would act to suppress star formation at early epochs (please refer to BCFL and SPF for the specifics on the differences in the two models). SPF use a semi-analytical modeling of galaxies in the CDM hierarchical clustering framework, adopting the $\Lambda CDM$ cosmology [$\Omega_0 = 0.3$, $\Omega_{\Lambda} = 0.7$, $h = H_0/(100 \ \text{km s}^{-1} \text{Mpc}) = 0.7$, $\sigma_8 = 1.0$] to understand the nature of Lyman break galaxies. Their models take into account the effects of the cooling rate of gas, supernovae feedback, galaxy-galaxy mergers, and star formation and subsequent evolution. They address the effects of dust extinction by following the recipe described in Wang & Heckman (1996) for nearby starbursts that returns the optical depth for a given extinguished UV luminosity, intrinsic UV luminosity, and face-on optical depth. They generate Monte Carlo–based merger trees in which each branch in the tree is associated with a merger. Within this framework, they considered three different models to represent the variety of star formation events. The “collisional starburst” model is one in which star formation occurs quiescently, with additional star formation occurring in bursts. The “constant efficiency quiescent” model involves only quiescent star formation with no bursts. And the “accelerated quiescent” model involves quiescent star formation but with the star formation rate increasing with look-back time. SPF conclude that of the three models, the “collisional starburst” model best reproduces the observations of the LBGs, including comoving number density, star formation rates, internal velocity dispersions and the observed luminosity function, global star formation rate density, and cold gas and metallicity abundances in the universe. Thus, they advocate that star formation occurred at a higher rate in the high-redshift universe and that mergers were responsible for increasing the star formation rate by triggering gas inflow to the central regions.

The positive color gradients we see at high redshifts would then be associated with nuclear starbursts induced by mergers and/or interactions, which could also cause star formation to “migrate” over time from the central regions to the spiral arms, where we see most of the star formation today; that is, when galaxies are first formed, the stars would tend to be born in the dense central regions. Then some galaxies may undergo mergers, which funnel gas to the central regions causing a burst of star formation. After awhile, the gas will be depleted and dispersed such that during the late stages of merger, the central light profiles will evolve to follow the $r^{1/4}$ law (Mihos, Richstone, & Bothun 1992; Negroponte & White 1983; Barnes 1992). During the late stages of the merger, the presence of a central bulge might suppress the inflow of gas and consequently reduce the star formation efficiency (Mihos & Hernquist 1994). Then if the galaxy experiences further interactions with another galaxy, material can rain in on the outer parts, causing the gas to collapse to form stars around the spheroid. Therefore, if the hierarchical structure formation scenario represents an accurate prediction of structure formation, at redshifts in the range $2.0 \leq z \leq 3.5$, we may be witnessing the epoch at which galaxies are experiencing mergers and their star formation is enhanced and centrally concentrated.

8. CONCLUSIONS

From our surface brightness and color analysis of galaxies at a range of redshifts probed at the same rest-frame wavelengths in the Hubble Deep Field North, we conclude as follows:

1. The color profiles of galaxies reveal that at earlier epochs there are fewer galaxies with old red stellar populations in their centers and most galaxies have centrally concentrated star formation. As in local samples of galaxies, our intermediate-redshift galaxies ($0.5 \leq z \leq 1.2$) have red-exponential profiles have slightly decreased. Our results also suggest a statistically insignificant increase in the fraction of galaxies with peculiar or irregular structure at higher redshifts. The results should be viewed with a note of caution, however, because of the small sample size and large uncertainties in the galaxy models, especially at small scale lengths and faint magnitudes.
3. If, as predicted by hierarchical galaxy formation models, mergers and interactions played an important role in the lifetime of these galaxies, such processes would be responsible for the positive color gradients indicative of centrally concentrated star formation seen in the high-redshift galaxies. SPF show that their “collisional starburst” model, in which bursts are triggered by mergers, best reproduces the observed properties of Lyman break galaxies and of the universe in general. Such centrally condensed nuclear starbursts are consistent with our observed trends in the color gradients. A good way to test whether the “collisional starburst” model holds is by applying the color-asymmetry diagram developed by Conselice, Bershady, & Gallagher (2000) to distinguish between starbursts driven by mergers and interactions from starbursts that were ignited by some other method.

Since the Hubble Deep Field represents only a small volume of space, we must be cautious in generalizing our results to the universe as a whole. We need to obtain more observations of high-redshift galaxies to measure critical quantities such as their virial masses and estimation of dust content. We also need to better understand how and to what degree observational selection comes into play when we compare galaxies at different redshifts. Given that we are now detecting fainter galaxies at higher redshifts and that instruments with multiobject spectroscopic capabilities in the near-IR and 8 m class telescopes are now readily available, much information will undoubtedly be unraveled in the near future concerning the nature of LBGs that will allow us to formulate a more robust theory on the formation and evolution of galaxies.

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