ON THE ASSEMBLY HISTORY OF EARLY-TYPE GALAXIES IN THE HUBBLE DEEP FIELD NORTH$^{1,2}$

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ABSTRACT

We present deep Keck spectroscopy for a sample of $I_{814} < 22.5$ field early-type galaxies selected morphologically in the redshift range $0.56 \leq z \leq 1.02$ in the Hubble Deep Field North (HDF-N). Using velocity dispersions determined from the Keck spectra in conjunction with structural parameters measured from the deep WFPC2 images we study the evolution of the $M/L_B$ ratio and the fundamental plane (FP) with redshift. For the majority of galaxies the trends observed are very similar to those determined earlier for rich clusters. The systematic offset between HDF-N galaxies and cluster galaxies is $\Delta \ln M/L_B = -0.14 \pm 0.13$, corresponding to an age difference of only $16 \pm 15\%$ at $\mathcal{z} = 0.88$. However, we find enhanced H$\delta$ absorption of equivalent width $4.0^{+0.9}_{-0.5}$ Å in the mean spectrum of the ten galaxies, indicating the presence of young stars. We infer that the galaxies have composite stellar populations, consisting of a low mass young component in addition to a dominating old component. As the bulk of the stellar mass must have formed at $z \gtrsim 2$ our results argue against formation scenarios involving major mergers of gas-rich disk systems at $1 \lesssim z \lesssim 1.5$, and we conclude that $z \sim 1$ early-type galaxies were either assembled at higher redshift or in mergers involving little gas. The ubiquitous enhanced Balmer lines and the presence of tidal features in two of the galaxies lend some support to the latter hypothesis. The main uncertainty in the analysis is the small sample; larger samples are needed to study the interplay between the evolution of stellar populations and morphology in detail.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

1. INTRODUCTION

As continued merging is a central prediction of hierarchical assembly models, much effort has been expended in attempting to detect a decline with redshift in the abundance of well-formed early-type galaxies (e.g., Im et al. 2002, Bell et al. 2003, Treu 2003). Present results are somewhat inconclusive, largely because of the lack of high resolution imaging data for sufficiently large samples, the difficulty disentangling luminosity evolution and changes in the number density, and the effects of large scale structure. The most comprehensive study to date is the analysis of a very large color-selected sample by Bellet et al. (2000). Two alternative routes to the formation history of field spheroidals have emerged in the past few years. Treu et al. (1999), van Dokkum et al. (2001) and others have attempted to constrain evolution in the fundamental plane (FP) differentially with respect to that observed in clusters. Differential tests are less sensitive to selection effects and provide valuable constraints on environmental trends expected in hierarchical models (e.g., Kauffmann 1996). Furthermore, the FP gives information on the mass-to-light ($M/L$) ratios of galaxies, which can be used to interpret the observed evolution of the luminosity function in terms of the underlying mass function. Again, current results are not yet conclusive. Field and cluster samples with $z < 0.5$ have similar $M/L$ ratios (Kochanek et al. 2000; van Dokkum et al. 2001; Treu et al. 2001), but there are indications that differences set in at higher redshift (Treu et al. 2002).

A second development follows the discovery by Menanteau, Abraham, & Ellis (2001) that $\sim 25\%$ of field early-type galaxies in the Hubble Deep Fields (HDFs) show color inhomogeneities such as blue cores, quantified by non-uniformity measures across the resolved HST image. Such abnormalities may indicate recent (merger-induced) star formation and, if so, their study offers a possible route to an in situ mass assembly rate (Benson, Ellis, & Menanteau 2002). A key question therefore is the extent to which spectroscopic diagnostics of recent activity are seen in distant early-type galaxies (e.g., Barger et al. 1996).

In this Letter, we address the spectroscopic properties of a representative sample of HST-selected early-type galaxies in the HDF-N, with a median redshift $z \sim 0.9$. First we investigate whether the $M/L$ ratios of field and cluster early-type galaxies diverge beyond $z \sim 0.5$, as suggested by the work of Treu et al. (2002). Secondly, we consider the evidence for recent star formation and mergers using spectroscopic diagnostics. As the HDF-N represents a small sample, we consider this an initial exploration of these issues, demonstrating the value of more ambitious surveys now possible with wide field spectrographs such as DEIMOS (Faber et al. 2002). We assume $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ throughout.

2. DATA

2.1. Sample Selection and Spectroscopy

Early-type galaxies in HDF-N were selected morphologically from the catalog of Ellis, Abraham, & Dickinson (2001). The reliability of the classifications is discussed in some detail by Menanteau et al. (1999). Our present sample comprises a subset with $I_{814} < 22.5$ and $z > 0.5$. Spectroscopic redshifts are available for almost all of the HDF-N sources to our limit from Cohen et al. (2000).

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Spectroscopic observations were conducted at the Keck I telescope using the Low Resolution Imaging Spectrograph (Oke et al. 1995) on 2000 March 29–30 and 2001 March 27–28. A 7 hour exposure in mediocre seeing was obtained in 2000 using the 600 lines mm\(^{-1}\) grating blazed at 7500 Å. Superior data were obtained in 2001 in good conditions, using the 600 lines mm\(^{-1}\) grating blazed at 1 Åm. Between exposures the galaxies were moved along the slit to facilitate sky subtraction. The latter 12 hour exposures provided the bulk of the data comprising 10 targets. The instrumental resolution \(\sigma_{\text{inst}} \approx 80 \text{ km s}^{-1}\) at 8000 Å. The spectral coverage is approximately 7300–9900 Å. The data were reduced following standard procedures for dithered multi-slit data; the reduction of approximately 7300–9900 Å. The data were reduced following standard procedures for dithered multi-slit data; the reduction of the data comprising 10 targets. The instrumental resolution \(\sigma_{\text{inst}} \approx 80 \text{ km s}^{-1}\) at 8000 Å. The spectral coverage is approximately 7300–9900 Å. The data were reduced following standard procedures for dithered multi-slit data; the reduction of a very similar dataset is explained in detail in van Dokkum & Franx (2003).

Internal kinematics were determined by fitting broadened template star spectra to the galaxy spectra. Fits were performed in real space, since S/N weighting and masking of spectral features is more troublesome in Fourier space (see, e.g., Kelson et al. 2000a for details). The template stars cover the wavelength range 3200–5200 Å at high resolution (see van Dokkum & Stanford 2003). Velocity dispersions were derived for 9/10 targets (Table 1). The uncertainties do not include a systematic error of \(\approx 8\%\) as determined from varying the fitting region, template stars, and the continuum filtering. The S/N in the spectra ranges from 12 to 26 per Å. Studies at low redshift have shown that for S/N\(\leq 15\) systematic effects begin to dominate the errors (e.g., Jørgensen, Franx, & Kjærgaard 1995), and we find that both the S/N and the formal errors indicate that the exposure time was just sufficient for measuring velocity dispersions of these faint galaxies.

### 2.2. Structural Parameters

For the FP analysis, effective radii \(r_e\) and effective surface brightnesses \(\mu_e\) were determined by fitting 2D \(r^{1/4}\) models convolved with the PSF to the \(I_{814}\) images (see, e.g., van Dokkum & Franx 1996; Kelson et al. 2000b). The drizzled “Version 2” data release of the HDF-N (Williams et al. 1996) was used for the analysis. We used four well exposed, non-saturated stars sampling the full spatial variation of the WFC2 field to approximate the true PSFs. The rms range in structural parameters is \(\approx 6\%\) in \(r_e\), and \(\approx 10\%\) in \(\mu_e\). The errors are highly correlated, and the rms uncertainty in the product \(r_e\mu_e^{1/8}\) which enters the FP is \(\approx 2\%\). Median values of \(r_e\) and \(\mu_e\) (in units of \(I_{814}\) magnitudes per square arcsecond) are listed in Table 1. To compare galaxies at different redshifts, surface brightnesses were converted to a common rest-frame band. For galaxies at \(z = 0.8 - 1\) the observed \(I_{814}\) band closely corresponds to the rest-frame B band; hence we transformed the \(I_{814}\) surface brightnesses to rest-frame B using the observed \(V_{806} - I_{814}\) colors, as explained in van Dokkum & Franx (1996).

### 3. Mean Ages from the Fundamental Plane

We determine the mean age of the stellar populations in \(z \approx 1\) early-type galaxies from the evolution of the mean \(M/L_B\) ratio (see Franx 1993). Although derivation of absolute ages from morphologically-selected samples is susceptible to progenitor bias (van Dokkum & Franx 2001), we can constrain the relative ages of field galaxies compared to those of cluster galaxies.

As demonstrated by, e.g., Treu et al. (2001), the evolving \(M/L_B\) ratio can be derived from samples spanning a large redshift range by calculating the offsets of individual galaxies from the prediction of the locally determined FP. The nearby FP of cluster galaxies has the form \(r_e \propto \sigma^{1.20} I_{814}^{0.80}\) in the B band (Jørgensen, Franx, & Kjærgaard 1996), which implies that \(M/L \propto \sigma^{0.50} r_e^{0.25} I_{814}^{0.25}\), assuming that early-type galaxies form a homologous family (Faber et al. 1987). Further assuming that the FP of distant field early-type galaxies has the same form as that in nearby clusters, the residual from the FP is related to an offset in \(M/L_B\) through

\[
\Delta M/L_B \propto \sigma^{1.50} r_e^{1.25} I_{814}^{-1.25}\]

(see van Dokkum et al. 2001).

The \(\Delta \ln M/L_B\) ratios of the HDF-N galaxies are shown as a function of redshift in Fig. 1(a). Included are cluster galaxies, local field galaxies, and the field sample at \(0.15 < z < 0.55\) from van Dokkum et al. (2001). We find \(\Delta \ln M/L_B \propto (-1.25 \pm 0.15) z\) for the full sample of field galaxies, compared to \(\Delta \ln M/L_B \propto (-1.12 \pm 0.11) z\) for clusters. Assuming the same rate of evolution for both samples and using the biweight estimator (Beers, Flynn, & Gebhardt 1990), we find a systematic offset between the HDF-N galaxies and cluster galaxies of \(-0.14 \pm 0.13\) in \(\ln M/L_B\). Assuming a Salpeter (1955) IMF and no systematic difference in metallicity, this offset corresponds to an age difference of \(16 \pm 15\%\) at \(z = 0.88\). The slow evolution of field galaxies that we measure strengthens conclusions from earlier work by Kochanek et al. (2000), Treu et al. (2001), and van Dokkum et al. (2001). Treu et al. (2002) find stronger evolution of \(\Delta \ln M/L_B \propto -1.68 \pm 0.37\) for their field galaxies.
Panel (a) shows the $\Delta \ln M/L_B$ ratios of individual early-type galaxies in the HDF-N (solid symbols), relative to the prediction from the FP of the nearby Coma cluster. Open circles show field galaxies from Faber et al. (1989) and van Dokkum et al. (2001); dots show cluster galaxies from Jørgensen et al. (1996), van Dokkum et al. (1998), and Kelson et al. (2000a). All data except those of Faber et al. were analyzed using the same procedures. For reference, the lines indicate stellar formation redshift of 3 (solid) and 1.5 (broken). In panel (b) we show the FP of field early-type galaxies edge-on, after correcting the surface brightnesses for the observed luminosity evolution of cluster galaxies. High redshift field and cluster galaxies follow very similar trends in both panels.

The similarity between cluster galaxies and field galaxies is remarkable in light of expectations from hierarchical galaxy formation models, which predict that field galaxies should be substantially younger than cluster galaxies. The Diaferio et al. (2001) models predict a difference of $\Delta \ln M/L_B \approx -0.6$ (see van Dokkum et al 2001), which is ruled out by the data.

4. EVIDENCE FOR RECENT MASS GROWTH

Two galaxies deviate significantly from the general trends in Fig. 1, suggesting they have young stellar populations. The object with the lowest $M/L_B$ ratio (17) is the only galaxy in our sample with a blue core (Menanteau et al. 2001), which is likely associated with an active nucleus (Hornschemeier et al. 2000, Sarajedini et al. 2000). In Fig. 2 we show the ultra-deep WFPC2 images of these galaxies, after subtracting the best fitting $r^{1/4}$ laws. Remarkably, both deviating objects have morphological signatures indicative of recent accretion or mergers. These features have surface brightness $I_{814} = 24.5 - 25$, and are detectable only because of the depth of the HDF images. None of the other seven galaxies show unambiguous deviations from axisymmetry. We conclude that there is tantalizing evidence for recent mass growth in the population of $z \approx 1$ early-type galaxies. Note that these anomalous objects were not excluded from the field vs. cluster comparison in § 3, although the $M/L_B$ ratios of these galaxies are highly uncertain (in particular for galaxy 17).

5. EVIDENCE FOR RECENT STAR FORMATION

Whereas $M/L_B$ ratios are sensitive to the luminosity weighted mean age of stellar populations, age-sensitive spectral diagnostics such as the H$\delta$ absorption line provide information on the presence of (small amounts of) young stars (e.g., Barger et al. 1996). In Fig. 3 we show the mean spectrum of the ten early-type galaxies in our sample, created by normalizing each spectrum at $\lambda_{rest} = 4050$ Å. The median redshift $z = 0.90$, and the biweight average is $z_{B1} = 0.86$. The S/N is...
non-uniform as the full wavelength region is not covered by every galaxy; it is highest (≈ 40) in the region near the Ca II H and K break. Shown for comparison is the coadded spectrum of 356 red galaxies at 0.30 < z < 0.35 in the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2003).

The mean spectrum clearly reveals prominent Balmer absorption lines in addition to weak [O II]3727 Å emission, in striking contrast to the color-selected, lower redshift SDSS spectrum. The equivalent widths are $W_{\lambda}(H\delta) = 4.0^{+0.9}_{-0.5}$ and $W_{\lambda}(\text{[O II]}) = -1.7^{+0.5}_{-1.1}$, using bandpass definitions of Fisher et al. (1998). Uncertainties were derived by bootstrap resampling; we note that Balmer absorption lines at levels consistent with the average value can be detected in almost all individual spectra, albeit with lower significance ($\approx 1.0$ Å; Table 1).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{spectrum.png}
\caption{Coadded rest-frame spectrum for 10 HDF-N early-type galaxies at z = 0.90. The Balmer absorption lines are clearly enhanced with respect to the (color-selected) z = 0.33 mean SDSS spectrum (Eisenstein et al. 2003). The SDSS spectrum is offset by 0.35 in $F_{\lambda}$.}
\end{figure}

6. DISCUSSION

Our small sample of HDF-N galaxies tells a complex tale: the similarity of the $M/L_B$ ratios with those of cluster galaxies on one hand contrasts with evidence for recent accretion and star formation on the other. The Balmer absorption strength of 4.0 Å is remarkably high, and exceeds the expectation from simple passive evolution of a single age population: taking $2 < z_{\text{form}} < 3$ as the formation epoch of stars in cluster and field galaxies (van Dokkum & Franx 2001, and § 3), the Vazdekis (1999) models predict $W_{\lambda}(H\delta) \approx 1.0$ Å for galaxies viewed at $z \approx 0.9$.

Our results can be explained consistently by postulating that a substantial fraction of the HDF-N galaxies experienced some recent star formation, but that the bulk of the stellar mass was formed at redshifts $z \gtrsim 2$. We used the Vazdekis (1999) models to generate composite spectra consisting of a pre-existing, 2.8 Gyr old population containing the bulk of the stellar mass and a low mass young component of varying age. Such models naturally produce strong effects in the H$\delta$ line and only modest changes in $\log M/L_B$. As an example, a 0.5 Gyr old secondary star burst containing 3% of the total stellar mass gives $W_{\lambda}(H\delta) = 3.5$ Å and $\Delta \log M/L_B = -0.18$, entirely consistent with the observations. We note that similar models have been proposed for nearby early-type galaxies by Trager et al. (2000).

It is difficult to unambiguously identify the physical origin of recent star formation in the HDF-N galaxies. Tidal features detected in two galaxies argue that at least in some cases the cause may be a merger or the capture of a satellite. The small mass associated with the young component argues against major mergers of gas-rich disk systems in the redshift interval $1.0 \lesssim z \lesssim 1.5$. Mergers between bulge-dominated, gas-poor systems are much more difficult to constrain, as they would not have a large effect on the $M/L_B$ ratios and do not develop well defined tidal tails (e.g., Barnes 1988). Such mergers have been observed in clusters (e.g., van Dokkum et al. 1999), and were recently invoked to explain the inferred evolution of the luminosity density of red field galaxies (Bell et al. 2003).

Of course, we cannot yet exclude the possibility that the small HDF-N sample is special. The stacked spectrum of 15 "old" Extremely Red Objects (ERO) presented by Cimatti et al. (2002) shows no evidence for enhanced Balmer absorption, suggesting significant variation in the properties of $z \approx 1$ early-type galaxies depending perhaps on how they are selected. Only by correlating morphologies, $M/L_B$ ratios, colors and spectral features of large samples is it likely that a quantitative assembly history for $z \approx 1$ early-type galaxies can be determined.

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