A \( z = 5.34 \) GALAXY PAIR IN THE HUBBLE DEEP FIELD\(^1\)

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Received 1998 August 12; revised 1998 August 31

ABSTRACT

We present spectrograms of the faint V-drop \((V_{606} = 28.1, I_{814} = 25.6)\) galaxy pair HDF 3-951.1 and HDF 3-951.2 obtained at the Keck II Telescope. In a recent study, Fernández-Soto, Lanzetta, & Yahil derive a photometric redshift of \(z_{\text{ph}} = 5.28^{+0.34}_{-0.41} \) (2 \( \sigma \)) for these galaxies; our integrated spectrograms show a large and abrupt discontinuity near \(7710 \pm 5 \) Å. This break is almost certainly due to the Ly\(\alpha\) forest because its amplitude (1 \(- f_{\text{long}}/f_{\text{short}} > 0.87\), 95% confidence limit) exceeds any discontinuities observed in stellar or galactic rest-frame optical spectra. The resulting absorption break redshift is \(z = 5.34 \pm 0.01\). Optical/near-IR photometry from the HDF yields an exceptionally red \((V_{606} - I_{814})\) color, consistent with this large break. A more accurate measure of the continuum depression bluward of Ly\(\alpha\) utilizing the imaging photometry yields \(D_A = 0.88\).

The system as a whole is slightly brighter than \(L_{1500}^*\) relative to the \(z \sim 3\) Lyman break population, and the total star formation rate inferred from the UV continuum is \(\approx 22 \, h_5^{-2} \, M_{\odot} \, \text{yr}^{-1}\) \((q_0 = 0.5)\) assuming the absence of dust extinction. The two individual galaxies are quite small (size scales \(\lesssim 1 \, h_5^{-1} \, \text{kpc}\)). Thus these galaxies superficially resemble the “building blocks” of Pascarelle and coworkers; if they remain bound system, the pair will likely merge in a timescale \(\sim 100 \, \text{Myr}\).

Key words: early universe — galaxies: distances and redshifts — galaxies: evolution — galaxies: formation — galaxies: individual (HDF 3-951.0)

1. INTRODUCTION

We are presently targeting photometrically selected faint galaxies for spectroscopic study at the Keck Telescopes with the goal of measuring redshifts and star formation rates at early cosmic epochs. Selecting high-redshift galaxies based on their continuum properties (cf. Weymann et al. 1998) is important and complements work on emission-line–selected galaxies at \(z \gtrsim 4.5\) found serendipitously (Dey et al. 1998a, 1998b) and from narrowband imaging (Cowie & Hu 1998; Hu, Cowie, & McMahon 1998). Studying galaxies at these high redshifts has important implications for tracing the formation of galaxies and large-scale structure, mapping the history of star formation, and understanding the chemical history of the universe.

The Hubble Deep Field (HDF; Williams et al. 1996) has galvanized a renewed effort at estimating photometric redshifts (e.g., Lanzetta, Yahil, & Fernández-Soto 1996; Sawicki, Lin, & Yee 1997; see also Hogg et al. 1998). The extremely deep multiband integrations through the crisp eye of the Hubble Space Telescope (HST), supplemented by several deep campaigns across the electromagnetic spectrum (e.g., at radio, submillimeter, far-infrared, and near-infrared wavelengths: Fomalont et al. 1997; Hughes et al. 1998; Rowan-Robinson et al. 1997; Hogg et al. 1997; Eisenhardt et al. 1996; Thompson et al. 1999), are an ideal data set with which to estimate redshifts based on broadband colors. High-redshift targets are robustly selected based on the redshifted Lyman break at \((1 + z) 912 \, \text{Å}\) and the redshifted Ly\(\alpha\) discontinuity at \((1 + z) 1216 \, \text{Å}\), causing the galaxies to effectively disappear, or “drop out,” at short wavelengths. \(U\)-band dropouts, corresponding to \(z \sim 3\), have been systematically studied by several groups (cf. Steidel et al. 1996b; Lowenthal et al. 1997; Spinrad et al. 1998; Bunker et al. 1998). \(B\)-band dropouts, corresponding to \(z \sim 4\), and \(V\)-band dropouts, corresponding to \(z \sim 5\), are beginning to be addressed (Dickinson 1998; Weymann et al. 1998; Dey et al. 1998b). Our present list of potential \(z > 4\) candidates (\(B\) and \(V\) dropouts) includes six galaxies with \(I_{814} < 26.5\) in the HDF (Fernández-Soto, Lanzetta, & Yahil 1998; AB scale used throughout\(^3\)). Their spectroscopic study, even with the large aperture of the Keck telescopes and dark sky of Mauna Kea, is clearly a technical

\(^{1}\) Based on observations at the W. M. Keck Observatory, which is operated as a scientific partnership among the University of California, the California Institute of Technology, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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\(^{3}\) The AB magnitude system (Oke 1974) is defined such that \(m_{\text{AB}} = -2.5 \log \left[ \frac{f}{\text{ergs cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}} \right] - 48.60\).
challenge. Weymann et al.’s (1998) confirmation of a galaxy at $z = 5.60$ illustrates that the $V$-drop technique works. A systematic survey, however, is necessary to assess that this population is not contaminated by lower redshift interlopers such as galaxies with extremely high equivalent width emission lines (e.g., [O II] λ3727) in the $I_{814}$ filter. We describe the observations of one $V$-drop system, HDF 3-951.0. Our data imply a redshift of $z = 5.34$ for this system, one of the highest redshifts yet measured and among the first systematically preselected galaxies at $z > 5$. Throughout this paper we adopt $H_0 = 50 \, h_{50}$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.5$ (0.1), and $\Lambda = 0$. For these parameters, 1° subtends 5.6 (10.2) kpc at $z = 5.34$, and the universe is only 820 Myr (1.56 Gyr) old, corresponding to a look-back time of 93.7% (90.6%) of the age of the universe. We present our observations in § 2 and our redshift determination in § 3; we discuss the galaxy’s inferred properties in § 4.

2. OBSERVATIONS

HDF 3-951.0 is a faint galaxy “pair,” comprising HDF 3-951.1 and HDF 3-951.2, near the edge of the WF3 CCD of the HDF. In Figure 1 we present F606W ($V_{606}$) and F814W ($I_{814}$) images of the galaxy. Extant photometry of this system is assembled in Table 1. Clearly the most outstanding photometric features of the composite (HDF 3-951.0) energy distribution are the nondetection at $U_{300}$ and $B_{450}$, the marginal detection in $V_{606}$, and the very red color in $V_{606} - I_{814}$. The energy distribution appears to flatten at longer wavelengths with $I_{814} - K \lesssim 2.0$. These colors qualitatively suggest a high-redshift, star-forming system with the Lyα forest attenuating the spectrum below $I_{814}$.

![Fig. 1 — HST F606W (left) and F814W (right) drizzled images of HDF 3-951.0, a $z = 5.34$ galaxy pair composed of HDF 3-951.1 (southwest, brighter) and HDF 3-951.2 (northeast, fainter). HDF 3-951.0 is located at $z = 12^h36^m59^s.65$, $\delta = 62^\circ12'19''03''$ (J2000.0). Images shown are 12' on a side, oriented as illustrated by the compass arrow. Drizzled images have a pixel scale of 0.04 pixel$^{-1}$. HDF 3-951.0 was targeted for spectroscopic study because of its very red $V - I$ color, attributable to the Lyα forest at high redshift. The increased noise at the top of the images derives from the fact that HDF 3-951.0 resides near the edge of the HDF.](image)

| Galaxy Component | $V_{606}$ | $I_{814}$ | $K$ | $\langle F_{1500} \rangle^a$ | $L_{1500} h_{50}^b$ | $M h_{50}^c$ |
|------------------|-----------|-----------|-----|----------------|----------------|----------|
| HDF 3-951.1 (brighter) | 28.68 | 26.20 | ... | 8.0 | 12.7 | 13 |
| HDF 3-951.2 (fainter) | 28.87 | 26.95 | ... | 4.0 | 6.3 | 6 |
| HDF 3-951.0 (sum) | 28.08 | 25.60 | $>23.6$ | 13.9 (14.4)$^d$ | 22.1 (22.9)$^d$ | 22 (23)$^d$ |

**Table 1: Photometry**

**Note.**—All magnitudes are in the AB system. Separation of component centers is 0.61. Optical isophotal magnitudes are from Williams et al. 1996. $2 \sigma$ limit on the near-IR magnitude is derived from ground-based observations with the Infrared Imager (Eisenhardt et al. 1996) for a dimensionless Gaussian with FWHM ≈ 1.20. HDF 3-951 is undetected in $U_{300}$ and $B_{450}$, implying $2 \sigma$ limiting magnitudes of $U_{300} > 28.2$ and $B_{450} > 28.9$. The small inconsistency in that $I_{814} < I_{814} - 0.5$ HDF 3-951.1 + HDF 3-951.2 is present in Williams et al. 1996 and likely derives from the faint magnitudes and close separations considered.

- $^a$ Flux density at 1500 Å, $F_{1500}$, is in units of $10^{-20}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ and is derived from $I_{814}$ assuming an $f_{\nu} \propto \nu^{0.6}$ spectrum for $I_{814} > 7710$ Å with no flux below 7710 Å. See text for details.
- $^b$ $L_{1500}$ is in units of $10^{40}$ ergs s$^{-1}$ Å$^{-1}$, calculated for $q_0 = 0.5$ using $F_{1500}$ values.
- $^c$ Star formation rates, in units of $M_\odot$ yr$^{-1}$, assume $q_0 = 0.5$ and a Salpeter IMF with 0.1 $M_\odot < M < 125 M_\odot$ (see Madau, Pozzetti, & Dickinson 1998 for details). For $q_0 = 0.1$, these rates are 3.3 times larger.
- $^d$ First value derives from photometry; second (parenthetical) value derives from spectrophotometry utilizing the continuum flux near 1350 Å and assuming an $f_{\nu} \propto \nu^{0.6}$ spectrum. See text for details.
and OB stars dominating the rest-frame UV past Lyα. A more detailed technique employing template spectra and maximum likelihood analysis yields a photometric redshift of $z_{ph} = 5.28^{+0.34}_{-0.41}$ (2 $\sigma$) for this system and $z = 5.72^{+0.33}_{-0.34}$ (2 $\sigma$) for HDF 3-951.1 alone (the brighter component; object 3 in Fernández-Soto, Lanzetta, & Yahil 1998; see also Lanzetta, Yahil, & Fernández-Soto 1996). Comparisons between photometric and spectroscopic redshift determinations show that the former is typically robust to $\Delta z \approx 0.34$ for objects with $I_{814} \approx 25.5$ and $z > 3$ (Fernández-Soto, Lanzetta, & Yahil 1998).

However, an accurate determination of the redshift requires deep spectroscopy, and so we observed the HDF during three observing runs in 1998 using the spectroscopic mode of the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) at the Cassegrain focus of the Keck II telescope. Only the data collected on UT 1998 February 19 were of high quality; UT 1998 January 20 suffered from poor seeing and high cirrus, while integrations on UT 1998 March 28 and 29 were plagued by poor seeing. All observations employed milled slit masks constructed to allow simultaneous observations of seven B- and V-dropout galaxies. The 1.5 wide slitlets were typically 20" long, allowing sufficient slit length for sky subtraction at the expense of a diminished number of targets. Slit-mask observations were made at a position angle of 102.7° (east of north) with the 400 line mm$^{-1}$ grating ($\lambda_{blaze} \approx 8500$ Å; $\Delta \lambda_{FWHM} \approx 11$ Å) sampling the wavelength range 5940–9720 Å. Small spatial shifts ($\approx 4''$) were performed between each $\approx 1800$ s exposure to facilitate the removal of fringing in the near-IR regions of the spectrograms.

All data reductions were performed using the IRAF package and followed standard slit spectroscopy procedures. Wavelength calibration was performed using an NeAr lamp, employing telluric lines to adjust the zero point. Flux calibration was performed using observations of G191B2B, Feige 34, HZ 44, and Wolf 1346 (Massey et al. 1988; Massey & Gronwall 1990), and accurate spectrophotometry was verified against the HDF photometry by convolving the spectra of HDF 3-951.0 and a brighter galaxy that serendipitously lay along one of the slitlets (HDF 3-493.0: $I_{814} = 21.74, z = 0.848$) with the F814W filter response function. HDF 3-951.0 was detected during all three observing runs. However, the February data (seeing photometric), comprising four integrations totaling $\approx 6900$ s, is of much higher signal-to-noise ratio; our final spectrum (Fig. 2) is composed from the February data alone.

![Fig. 2.](image_url) Spectrum of the color-selected galaxy HDF 3-951.0 at $z = 5.34$. Top spectrum is smoothed with a 5 pixel boxcar filter, bottom spectrum is co-averaged in 10 pixel bins with 1 $\sigma$ error bars assigned according to sky counts. The total exposure time is 6900 s, and the spectrum was extracted using an 1.3 $\times$ 1.5 aperture. Horizontal bars on the bottom panel indicate the wavelength region considered for determination of $D_A$. 
3. REDSHIFT DETERMINATION

Our final spectrogram of the unresolved pair of faint galaxies (Fig. 2) yields a fairly noisy but robust result: above 7720 Å there is a roughly flat continuum (in $f_\nu$) with a mean flux near 0.4 µJy. Almost no light is detected below 7700 Å ($f_\nu < 0.05$ µJy), and an accordingly large and abrupt discontinuity exists at 7710 ± 5 Å. An accurate measurement of the discontinuity wavelength is made difficult by the faintness and separation of HDF 3-951.1 and HDF 3-951.0, as well as et al.’s confirmation of HDF 3-951.0 at $z = 5.34 ± 0.01$. The systematics of Lyγ absorption might provide a systematic redward bias of Δ$z \approx 0.01$—in high-redshift galaxies, associated and foreground absorption generally displaces Lyγ emission lines redward of their host galaxy systemic velocity by up to several hundred km s$^{-1}$. In fact, this mechanism also imprints an asymmetry onto the Lyγ emission line, when present, thus providing a powerful discriminant between high-redshift Lyγ and low-redshift objects (Dey et al. 1998a).

We therefore associate the break with the Lyα forest, implying a redshift $z = 5.34 ± 0.01$. The systematics of Lyγ absorption might provide a systematic redward bias of Δ$z \approx 0.01$—in high-redshift galaxies, associated and foreground absorption generally displaces Lyγ emission lines redward of their host galaxy systemic velocity by up to several hundred km s$^{-1}$. In fact, this mechanism also imprints an asymmetry onto the Lyγ emission line, when present, thus providing a powerful discriminant between high-redshift Lyα and low-redshift objects (Dey et al. 1998a). The sharpness of the discontinuity and the flatness of the longer wavelength spectrogram (in $f_\nu$) are further arguments for identifying the break with the Lyα forest onset. For the remainder of this paper we adopt $z = 5.34$ for the redshift of the faint galaxy pair HDF 3-951.0.

4. DISCUSSION

Our deep spectroscopy confirming the high redshift of HDF 3-951.0, as well as Weymann et al.’s (1998) confirmation of HDF 4-473.0 at $z = 5.60$, illustrate that the photometric redshift technique, and, in particular, $V$-drop selection, is a robust method for selecting and studying the distant universe. We now derive some basic physical properties of HDF 3-951.0, consonant with its faint magnitude.

If the UV continuum is dominated by light from young, hot stars, the star formation rate ($M$) may be derived from the UV flux at $\lambda_0 \approx 1240$ Å. Assuming the continuum emission from HDF 3-951.0 is unreddened and has a spectral slope of $f_\nu \propto \lambda^2$, consistent with the observations, we derive $L_{1500} = 22.9 \times 10^{40} h_{50}^{-2}$ ergs s$^{-1}$ Å$^{-1}$ and $M_{1500} = -21.5$ AB mag for HDF 3-951.0 based on the flux density between 8000 and 9000 Å (see Table 1). Madau, Pozzetti, & Dickinson (1998) calculate $M \approx 10^{-40} L_{1500} M_\odot$ yr$^{-1}$ for $L_{1500}$ measured in units of ergs s$^{-1}$ Å$^{-1}$ and a more than 100 Myr old population with a Salpeter initial mass function (IMF) (0.1 $M_\odot < M < 125 M_\odot$). This is roughly consistent with the relation derived from the Leitherer & Heckman (1995) models for a different IMF and much younger ages of less than 10 Myr. These conversions are meant to be illustrative rather than definitive; they depend on the assumed star formation history, IMF, metallicity, and age. The lower limit on the inferred star formation rate for HDF 3-951.0 is thus $\approx 22 h_{50}^{-2} M_\odot$ yr$^{-1}$, assuming the absence of dust absorption. Dickinson (1998) finds that the ultraviolet luminosity function of Lyman-break galaxies at $z \approx 3$ is well modeled by a Schechter luminosity function of characteristic absolute magnitude $M^*_{1500} \approx -21$ AB mag. This implies that the HDF 3-951.0 galaxies are individually subluminous but slightly brighter than $L^*_{1500}$ when considered as a single system uncorrected for extinction.

The star formation rates may also be determined for the galaxy pair individually utilizing the imaging photometry, without reference to the spectrophotometry. Assuming a Heaviside function spectrum with $f_\nu = 0$ below 7710 Å and $f_\nu \propto \lambda^2$ redward of 7710 Å, the $I_{814}$ magnitudes may be...
used to calculate an upper limit on the flux density redward of Lyα. This then yields $F_{1500}$ and, with the above prescription, the inferred star formation rate (see Table 1). We find $M = 13 h_{50}^2 M_\odot$ yr$^{-1}$ for HDF 3-951.1 and $M = 6 h_{50}^2 M_\odot$ yr$^{-1}$ for HDF 3-951.2.

The flat red end of the spectrum of HDF 3-951.0 is similar to the spectra of $z \approx 3$ Lyman break galaxies (cf. Steidel et al. 1996b)—systems that are well represented by an OB stellar population with little dust. Deep Keck/LRIS spectroscopy of some of the brighter $z \approx 3$ Lyman break population suggests that galaxies with Lyα in emission are generally flatter in $f_{\lambda}$ at 1220–1700 Å, while those galaxies with Lyα in absorption are generally redder at these wavelengths (Spinrad et al. 1998). From a study of vacuum-UV IUE spectra of local starburst galaxies, Heckman et al. (1998) find that metal-rich starbursts are redder and more heavily extinguished (have larger values of $L_{\text{IR}}/L_{\text{UV}}$), have stronger rest-frame UV absorption lines, and occur in more massive and brighter host galaxies. Similarly, the brightest Lyman break galaxies tend not to have Lyα in emission (C. C. Steidel 1998, private communication), possibly a result of the galaxies’ lying in deeper potential wells and thus being more able to retain gas and dust which scatter and absorb the Lyα photons and redden the $\lambda > 1220$ Å continuum. In this scenario, the apparent flatness of our HDF 3-951.0 spectrum at $\lambda > 1300$ Å is inconsistent with the lack of a measurable Lyα emission line. However, relatively small column densities of neutral gas with even very small dust content can destroy Lyα emission if this gas is static with respect to the ionized region where Lyα photons originate (cf. Kunth et al. 1998).

HDF 3-951.0 is potentially reddened by foreground and associated dust, consistent with the lack of Lyα emission; our ground-based limits on the near-IR magnitude of the system constrains $E_{B-V} \lesssim 0.3$ (for a dust-free Heaviside spectrum subject to extinction by a foreground screen of dust following the extinction law of Cardelli, Clayton, & Mathis 1989). This level of extinction would imply intrinsic star formation rates $\sim 45\%$ higher than the values quoted above. A real measurement of the dustiness of the galaxy pair must await deep near-IR images of the field, as have recently been obtained with NICMOS on the HST.

We next consider the $I_{814}$ morphology of this system (see Fig. 3). The FWHM of HDF 3-951.1 and HDF 3-951.2 are 0.50 and 0.28, respectively. Comparison with a star reveals that both are clearly resolved (FWHM$_{\text{star}} = 0.14$) with deconvolved half-width, half-maxima of 0.24 and 0.12, respectively. For $q_0 = 0.5 (0.1)$, these correspond to 1.3 (2.5) $h_{50}^2$ kpc for HDF 3-951.1 and 0.7 (1.2) $h_{50}^2$ kpc for HDF 3-951.2, comparable to the values found for many of the $z \approx 3$ Lyman-break galaxies (Giavalisco, Steidel, & Macchetto 1996). HDF 3-951.1 (the brighter component) contains substructure, with a second “hot spot” $\sim 0.12$ east of the core, at a projected separation of 0.66 (1.2) $h_{50}^2$ kpc. We speculate that this is either a knot of star formation (bright in the rest-frame UV) or evidence of multiple nuclei. The projected proximity of HDF 3-951.2 adds weight to the hypothesis that this is a dynamically bound system and that we are witnessing a merger event. Lyman-break galaxies at $z \approx 3$ often exhibit either disrupted morphologies or multiple components (e.g., Giavalisco, Steidel, & Macchetto 1996; Steidel et al. 1996a; Bunker et al. 1998).

Because of the substructure of its core, HDF 3-951.1 is not well fitted by either a de Vaucouleurs $r^{1/4}$ law or an exponential surface brightness profile. The exponential disk appears to dominate in a two-component model, and the scale length is 0.23, equivalent to $r_{\text{disk}} = 1.3 (2.3) h_{50}^{-1}$ kpc. The elongation is $b/a = 1.2$.

The fainter HDF 3-951.2 is well fitted by an exponential disk profile, with a scale length of 0.12, corresponding to

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**Fig. 3.**—Detail of the drizzled F814W ($I_{814}$) image of HDF 3-951.0 (left) and surface brightness profiles for the individual components (right). The scaled surface brightness profile of a star is illustrated (open diamonds); both components of HDF 3-951.0 are clearly resolved. Note that the brighter component (HDF 3-951.1; solid circles) has a substructure to the east, possibly indicative of a recent or ongoing interaction. The surface brightness profile clearly illustrates this substructure. The fainter component (HDF 3-951.2; open triangles) is well fitted by an exponential disk profile. The flatness of the surface brightness profiles at small ($\lesssim 0.05$) radii are the result of sampling the same pixel, and at large radii ($\gtrsim 0.3$) the profiles of the galaxies are contaminated by their respective neighbors.
0.65 (1.2) $h^{-1}_{50}$ kpc, and is almost circular ($b/a = 1.1$). As with the $z \approx 3$ population, we note that HDF 3-951 is significantly more compact at rest-frame UV wavelengths compared with local disk galaxies, which have typical scale lengths of ~5 kpc at optical wavelengths (Freeman 1970).

The angular separation of 0'061 projects to 3.4 (6.2) $h^{-1}_{50}$ kpc for $d_0 = 0.5$ (0.1), implying that HDF 3-951.0 is a pair of subluminous systems of modest projected separation. What can we say about the evolutionary fate of HDF 3-951.0? Given the small physical sizes and projected separation, in all likelihood HDF 3-951.1 and HDF 3-951.2 will merge into a single galaxy. Assuming a relative velocity of 2622 km s$^{-1}$ and a physical separation equal to the projected $\approx 5$ kpc, the crossing time is $\approx 25$ Myr. Thus we estimate that the merger timescale for HDF 3-951.1 and HDF 3-951.2 is a few crossing times (cf. Barnes & Hernquist 1996), or $\sim 100$ Myr. Indeed, we suggest that HDF 3-951.1 and HDF 3-951.2 are already in the process of merging; we are perhaps witnessing the galaxies in a postcollision state, with the luminosity enhanced by merger-induced star formation. Studies of low-redshift merging systems find enhanced rates of star formation (Sanders et al. 1988), consistent with the apparently OB star-dominated spectrum of HDF 3-951.0. We note that our $I_{814}$ images sample the rest-frame UV. Even in present-day galaxies, UV-emitting regions in galaxies are typically small. Alternatively, two regions of active star formation within $\approx 5$ kpc of each other may well be star-forming knots within the same galaxy. Longer wavelength imaging will help resolve this question. Indeed, preliminary reductions of NICMOS observations of the HDF suggest that these objects remain separate in F160W images (rest-frame $\sim 2500$ Å; M. E. Dickinson 1998, private communication). We note, finally, that the size and luminosity of HDF 3-951.0 suggest it to be a more distant version of the $z \approx 2.4$ galaxies discussed by Pascarelle et al. (1996), which have typical half-light radii of 0'1-0'2.

What are the implications of the large continuum discontinuities in the Ly$\alpha$ region? How reliable is the nominal factor of 10 at 95% confidence level we suggest, and how does it propagate to the parameter $K$? The apparent systematic displacement of the Zuo & Lu (1993) points likely derives from their revised approach for determining the continuum blueward of Ly$\alpha$: employing high signal-to-noise, high-resolution spectra, they model and replace the Ly$\alpha$ forest absorption features.

(born out by our spectra to date) that the $f_\nu$ flux distributions above and below Ly$\alpha$ are flat. We assume a two-step spectral energy distribution with zero flux below the Lyman limit, $f_\nu^*$, between the Lyman limit and Ly$\alpha$, and $f_\nu^\ast$ redward of Ly$\alpha$. For $f_\nu^* \approx \lambda^{0.5}$, 54% of the F606W flux comes from $\lambda > 5782$ Å (the Lyman limit at $z = 5.34$) and 48% of the F814W flux comes from $\lambda > 7710$ Å (Ly$\alpha$ at $z = 5.34$). For the observed magnitudes of HDF 3-951.0, this implies $f_\nu^* = 0.04$ $\mu$Jy and $f_\nu^\ast = 0.33$ $\mu$Jy. The resultant “photometric Ly$\alpha$ discontinuity” with $V-I = 2.50$ is $D_{\alpha}^{\text{phot}} = 0.88$. This agrees with the break amplitude derived from the Keck spectrogram and is much higher than previously reported values of $D_{\alpha}$ (see also Dey et al. 1998a, 1998b).

In Figure 4 we present recent measurements of $D_{\alpha}$ from spectra of quasars and high-redshift galaxies, where HDF 3-951.0 is indicated by the more robust photometric measurement. The Weymann et al. (1998) points utilize their photometry, corrected for the Ly$\alpha$ emission line flux of $1.0 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$, and an $f_\nu \propto \lambda^k$ spectrum fit to the NICMOS near-IR brightnesses (top point). The lower Weymann et al. (1998) point utilizes an $f_\nu \propto \lambda^{-0.4}$ spectrum, corresponding to their best-fit semimipirical model.

Our concern about the break amplitude arises from its strength: Madau’s (1995) theoretical estimate of the contribution of the Ly$\alpha$ forest to $D_{\alpha}$ is only $\sim 0.79$ at $z = 5.34$ and $\sim 0.83$ at $z = 5.60$. This extrapolation assumes a distribution of high and low optical depth foreground Ly$\alpha$ clouds causing Lyman series absorption in the spectrum of a distant quasar or galaxy. The scatter around the Madau curve is substantial, even at lower redshifts, so the high values of $D_{\alpha}$ at $z > 5$ may simply reflect the usual scatter observed in that parameter. However, at large enough redshift our line of sight must penetrate the end stages of reion-
zation (cf. Loeb 1998; Miralda-Escudé & Rees 1997), where a smooth distribution of neutral hydrogen gas will cause an additional Gunn-Peterson H α opacity at λ < 1216 Å. Whether this starts at z = 5 or z ≳ 10 remains an intriguing question. Are we seeing the first hints of the Gunn-Peterson trough in these distant systems? If we see enhanced (Gunn-Peterson) absorption shortward of Lyα for their invaluable assistance during our observing runs at the W. M. Keck Observatory. We are grateful to A. Philips for providing software and assistance in slit-mask construction and alignment and J. Cohen for supporting LRIS; and to M. Dickinson, E. Gawiser, J. R. Graham, C. Manning, F. Marleau, and C. Steidel for useful comments. We also thank the referee, D. W. Hogg, for timely and constructive comments. H. S. acknowledges support from NSF grant AST 95-28536, D. S. acknowledges support from IGPP grant 99-AP026, A. B. acknowledges support from a NICMOS postdoctoral fellowship, A. D. acknowledges support from NASA grant HF-01089.01-97A, K. L. acknowledges support from NASA grant NAGW-4422 and NSF grant AST 96-4216, and A. F.-S. acknowledges support from an Australian ARC grant.

We thank J. Aycock, W. Wack, R. Quick, T. Stickel, G. Punawai, R. Goodrich, R. Campbell, T. Bida, and B. Schaeffer for their invaluable assistance during our

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