PHOTOMETRIC CONSTRAINTS ON THE REDSHIFT OF $Z\sim 10$ CANDIDATE UDFJ-39546284 FROM DEEPER WFC3/IR+ACS+IRAC OBSERVATIONS OVER THE HUDF¹

R. J. BOUWENS^{2,3}, P. A. OESCH^{3,†}, G. D. ILLINGWORTH³, I. LABBÉ², P. G. VAN DOKKUM⁴, G. BRAMMER⁵, D. MAGEE³, L.R. SPITLER^{7,8}, M. FRANX², R. SMIT², M. TRENTI⁶, V. GONZALEZ^{3,9}, C. M. CAROLLO¹⁰

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ABSTRACT

Ultra-deep WFC3/IR observations on the HUDF from the HUDF09 program revealed just one plausible $z \sim 10$ candidate UDFj-39546284. UDFj-39546284 had all the properties expected of a galaxy at $z \sim 10$ showing (1) no detection in the deep ACS+WFC3 imaging data blueward of the F160W band, exhibiting (2) a blue spectral slope redward of the break, and showing (3) no prominent detection in deep IRAC observations. The new, similarly deep WFC3/IR HUDF12 F160W observations over the HUDF09/XDF allow us to further assess this candidate. These observations show that this candidate, previously only detected at $\sim 5.9\sigma$ in a single band, clearly corresponds to a real source. It is detected at $\sim 5.3\sigma$ in the new H_{160} -band data and at $\sim 7.8\sigma$ in the full 85-orbit H_{160} -band stack. Interestingly, the non-detection of the source ($< 1\sigma$) in the new F140W observations suggests a higher redshift. Formally, the best-fit redshift of the source utilizing all the WFC3+ACS (and IRAC+ K_s band) observations is 11.8 ± 0.3 . However, we consider the $z \sim 12$ interpretation somewhat unlikely, since the source would either need to be $\sim 20 \times$ more luminous than expected or show very high-EW Ly α emission (which seems improbable given the extensive neutral gas prevalent early in the reionization epoch). Lower-redshift solutions fail if only continuum models are allowed. Plausible lower-redshift solutions require that the H_{160} -band flux be dominated by line emission such as $H\alpha$ or [OIII] with extreme EWs. The tentative detection of line emission at $1.6\mu m$ in UDFj-39546284 in a companion paper suggests that such emission may have already been found.

Subject headings: galaxies: evolution — galaxies: high-redshift — galaxies:individual:UDFj-39546284

1. INTRODUCTION

As the identification of large numbers of $z\sim 8$ galaxies becomes more routine in deep HST observations (e.g., Bouwens et al. 2011b; Oesch et al. 2012b; Bradley et al. 2012; Lorenzoni et al. 2011), the high-redshift frontier has clearly moved to $z\sim 9$ -10. Only a small number of $z\sim 9$ -10 candidates are known to date (Bouwens et al. 2011a, 2013; Oesch et al. 2012a; Zheng et al. 2012; Coe et al. 2013; Ellis et al. 2013). The quantitative study of $z\sim 9$ -10 galaxies provides us with our greatest possible leverage for characterizing the growth rate of galaxies from early times, clarifying the role that galaxies played in reionizing the universe, and assessing possible changes in the stellar populations at very low, even primordial, metallicities.

 2 Leiden Observatory, Leiden University, NL-2300 RA Leiden, Netherlands

³ UCO/Lick Observatory, University of California, Santa Cruz, CA 95064

Cruz, CA 95064

⁴ Department of Astronomy, Yale University, New Haven, CT 06520

⁵ European Southern Observatory, Alonso de Córdova 3107, Casilla 19001, Vitacura, Santiago, Chile

⁶ Kavli Institute for Cosmology and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

Operation of Physics & Astronomy, Macquarie University, Sydney, NSW 2109 Australia

⁸ Australian Astronomical Observatory, PO Box 296 Epping, NSW 1710 Australia

⁹ Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA

 10 Institute for Astronomy, ETH Zurich, 8092 Zurich, Switzerland

[†] Hubble Fellow

Of all the $z\sim9$ -10 candidates, perhaps the most tantalizing is the $z\gtrsim10$ candidate UDFj-39546284. UDFj-39546284 was initially identified as a promising $z\sim10$ candidate by Bouwens et al. (2011a) making use of the ultra-deep optical and near-IR observations over the HUDF from the full HUDF09 data set (see also Oesch et al. 2012a). More recently, UDFj-39546284 was re-examined using the WFC3/IR observations from the HUDF12 and CANDELS programs by Ellis et al. (2013), and it was found to be undetected in the F140W band, suggesting that its redshift could be as high as $z\sim11.9$.

In this paper, we perform a detailed reassessment of UDFj-39546284 taking advantage of several additional data sets. In addition to utilizing the new ultra-deep WFC3/IR observations from the 128-orbit HUDF12 (Ellis et al. 2013; Koekemoer et al. 2013) and CANDELS (Grogin et al. 2011; Koekemoer et al. 2011) programs and deep IRAC observations already considered, we use a deeper reduction of the optical observations over the HUDF from the XDF dataset (Illingworth et al. 2013) than previously used. Furthermore, we add new constraints from a deep K_s -band image, add new measurements of size/structure, and present the source in the context of the expected UV LF at z > 10 in a quantitative way. Finally, we make use of results from a companion paper (Brammer et al. 2013) on deep WFC3/IR grism spectroscopy of the source to further clarify its nature.

The plan for this paper is as follows. In §2, we provide a brief summary of the observational data. In §3, we present the HST photometry we have for the source and use these observations to reassess its nature. Fi-

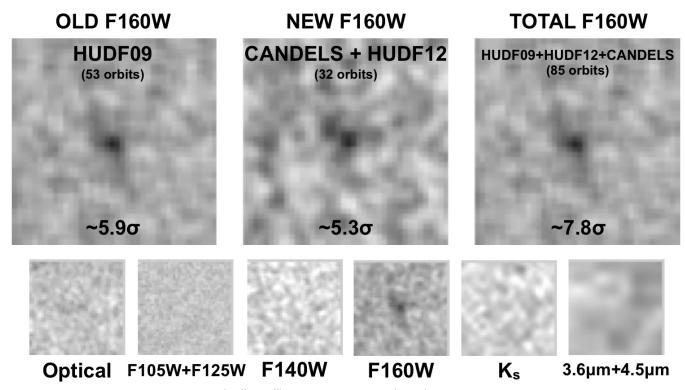


FIG. 1.— H_{160} -band imaging observations $(2.4'' \times 2.4'')$ of the Bouwens et al. (2011a) $z \sim 10$ candidate UDFj-39546284 in the original 53-orbit HUDF09 observations (upper-left panel), the new 32-orbit HUDF12+CANDELS observations (upper-middle panel), and the combined 85-orbit observations (upper-right panel). Indicated in the lower part of each panel is the significance level at which the source is detected in the H_{160} -band observations (0.5"-diameter apertures). This source consists of a bright core embedded in a larger structure extending up to 0.4" in radius from the core. The morphology of UDFj-39546284 is similar to a z = 1.61 [OIII] blob recently identified by Brammer et al. (2013). The lower panels show images of UDFj-39546284 in the optical/ $B_{435}V_{606}i_{775}I_{814}z_{850}$, $Y_{105}+J_{125}$, JH_{140} , H_{160} , K_s , and 3.6μ m+4.5 μ m bands.

nally, in §4, we summarize our results. We refer to the HST F435W, F606W, F775W, F814W, F850LP, F105W, F125W, F140W and F160W bands as B_{435} , V_{606} , i_{775} , I_{814} , z_{850} , Y_{105} , J_{125} , JH_{140} , and H_{160} , respectively. Where necessary, we assume $\Omega_0=0.3$, $\Omega_{\Lambda}=0.7$, $H_0=70\,\mathrm{km/s/Mpc}$. All magnitudes are in the AB system (Oke & Gunn 1983).

2. OBSERVATIONAL DATA AND PHOTOMETRY

2.1. Observational Data

We analyze the full set of HST observations over the HUDF09/XDF, including data from the 192-orbit HUDF09 program (Bouwens et al. 2011b), CANDELS, the 128-orbit HUDF12 program, and several other sizeable programs.

255 orbits of HST WFC3/IR observations are now available over the HUDF09/XDF, including ~ 100 , ~ 40 , 30, and ~ 85 orbits in the Y_{105} , J_{125} , JH_{140} , and H_{160} bands, respectively. The biggest gains over the HUDF09 program came in the Y_{105} and JH_{140} bands. We reduced these observations in a similar manner as the original WFC3/IR data from the HUDF09 program (Bouwens et al. 2011b). Special care was taken to keep our reductions of the new CANDELS and HUDF12 observations separate from those of the original HUDF09 data, to enable us to evaluate the reality of sources from the original observations.

In addition, we now have new reductions of the optical observations over the HUDF from the XDF project that are ~ 0.1 -0.2 mag deeper than the original Beckwith et al. (2006) HUDF reductions due to our inclusion of all

other HST data sets taken over the HUDF for the past 10 years, including the recent optical/ACS I_{814} data.

To obtain photometric constraints on UDFj-39546284 redward of the H_{160} -band, we utilize the deep 120-hour Spitzer/IRAC (Fazio et al. 2004) observations in the [3.6] and [4.5] channels from the original GOODS IRAC program and the 262-hour IRAC Ultradeep Field program (IUDF10: PI: Labbé). These observations reach to 27.1 mag and 26.8 mag in the $3.6\mu m$ and $4.5\mu m$ bands, respectively (3σ : Labbé et al. 2012). We also utilize the very deep K_s -band observations over the HUDF (26.5 mag: 5σ), including data from VLT/HAWK-I (program 186.A-0898, PI A. Fontana), VLT/ISAAC (program 73.A-0764 PI I. Labbé and 168.A-0485 PI C. Cesarsky), and PANIC (PI I. Labbé). In coadding the K_s -band observations, individual frames are weighted by the inverse variance expected for a point source (Labbé et al. 2003). Table 1 provides detailed information on the various K_s -band observations used for our deep reduction.

In summary, in addition to the HUDF09/HUDF12 WFC3/IR and the IUDF10 IRAC datasets (also used by Ellis et al. 2013, though Ellis et al. 2013 appear not to have accounted for the modest variations in the effective depth of the IRAC observations due to varying contamination from neighboring foreground sources), we utilize the deeper XDF optical/ACS dataset on the HUDF, deep optical/ACS I_{814} and deep K_s -band observations for our detailed study of UDFj-39546284.

2.2. Methodology for Doing Photometry

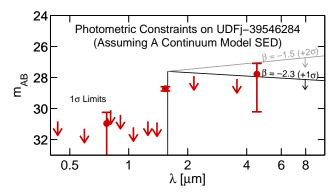


Fig. 2.— Photometric constraints on the SED of UDFj-39546284. The solid red points and error bar show the flux measurements, with 1σ uncertainties, and 1σ upper limits. The source is ourse shows a very large decrement between the H_{160} band. The source shows a very large decrement between the H_{160} band and the JH_{140} band (>2.2 mag). The dark and light gray lines show the 1σ and 2σ upper limits, respectively, that can be set on the spectral slope β redward of the break at $\sim\!\!1.6\mu\mathrm{m}$, assuming a continuum-model SED. The limits redward of the H_{160} -band show that UDFj-39546284 is blue in color and not red.

We obtain flux measurements on the HST observations by running SExtractor (Bertin & Arnouts 1996) in dualimage mode, taking the detection image to be the H_{160} -band and using the PSF-matched images for photometry. Colors are measured in small-scalable apertures (Kron [1980] factor of 1.2) and corrected to total by comparing the H_{160} -band flux in a larger-scalable aperture (Kron factor of 2.5) to that in the smaller-scalable aperture and then applying a correction to account for light on the wings of the PSF based on the tabulated encircled-energy distribution.

The K_s -band flux measurement was performed in a 0.65"-diameter circular aperture and corrected to match our HST photometry by comparing the H_{160} -band flux (0.65"-diameter aperture, after PSF-correction) to that found in our baseline scalable apertures.

IRAC photometry was performed utilizing software to model the light profiles of neighboring sources so that this light could be subtracted (Labbé et al. 2006, 2010a, 2010b, 2012). Clean photometry of the source is then performed (1.8"-diameter circular apertures). A factor of \sim 2.2 correction is made to the measured fluxes to account for light on the wings of the IRAC PSF.

3. RESULTS

3.1. Photometric Constraints on UDFj-39546284

The photometry we derive for UDFj-39546284 is presented in Table 1 and Figure 2. UDFj-39546284 again shows a very significant detection in the H_{160} -band and no significant detection in any other band. The fact that the source is detected in the new H_{160} -band observations at 5.3σ (0.5"-diameter aperture) and 7.8σ (0.5"-diameter aperture) in the total H_{160} -band stack demonstrates that this is definitely a real galaxy (Figure 1).

The present color measurements are consistent with those from Ellis et al. (2013), but our total H_{160} -band magnitude is ~ 0.6 mag brighter than the 0.5"-diameter aperture-magnitude measurement from Ellis et al. (2013). This is not unsurprising given the significant spatial extension of UDFj-39546284, our use of larger scalable apertures (more appropriate for this source), and our correction to total magnitudes.

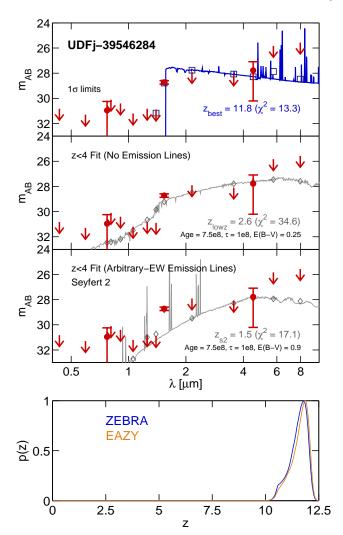


Fig. 3.— The flux constraints shown in the top three panels are as in Figure 2. The upper panel shows the best-fit SED at high redshift with $z_{phot}=11.8\pm0.3$ for a source without Lyx emission. The upper-middle panel shows the poor, but best low-redshift fit $(z_{lowz}=2.6,$ modest reddening E(B-V)=0.25) to the available photometry without invoking emission lines. The lower-middle panel shows the best low-redshift solution, allowing for the inclusion of arbitrary-EW emission lines from an AGN (Seyfert 2), with $z_{s2}=1.5,$ reddening E(B-V)=0.9, and ${\rm H}\alpha$ EWo $\sim5000\mbox{Å}.$ None of these "solutions" is especially likely (see text). The lowest panel shows the derived redshift likelihood distributions using the ZEBRA and EAZY photometric redshift codes.

The optical and near-IR observations blueward of the H_{160} -band are very deep and indicate a sharp fall-off in the spectrum at $<1.6\mu\mathrm{m}$ (Figure 2). The amplitude of the flux decrement from the H_{160} -band flux measurement is a substantial >2.8 mag to a coadded $Y_{105}J_{125}JH_{140}$ bandpass, >3.3 mag to a coadded $B_{435}V_{606}i_{775}I_{814}z_{850}Y_{105}J_{125}JH_{140}$ bandpass, and >2.2 mag to the JH_{140} -band. (The flux constraints from multiple bands were combined assuming a flat-spectrum (F ν) source.) Redward of the H_{160} -band, the IRAC and K_s -band observations are less deep, but place strong constraints on the general shape of the SED.

The existence of a significant $\sim 8\sigma$ detection of UDFj-39546284 in the H_{160} -band, a strong break in the spectrum blueward of the H_{160} -band, and no prominent detection of the source redward of the H_{160} -band is sug-

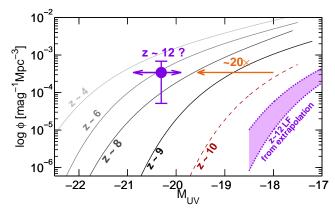


FIG. 4.— UDFj-39546284 is extremely luminous, if it is a $z\sim12$ galaxy. Shown is the constraint on the $z\sim12$ LF we would derive, if UDFj-39546284 were genuinely a $z\sim12$ star-forming galaxy. The effect of the photometric-redshift uncertainties $z=11.8\pm0.3$ on the inferred luminosity are indicated by the horizontal arrows. For context, the $z\sim4$ -10 LFs presented in Bouwens et al. (2007), Oesch et al. (2012a), and Oesch et al. (2013) are also shown. UDFj-39546284 is much more luminous, by a factor of $\sim\!10$, than comparably-prevalent galaxies at $z\sim10$ (i.e., with the same volume density). The luminosity of UDFj-39546284 is even more anomalous compared to the LF extrapolated to $z\sim12$ using $z\geq6$ and $z\geq8$ LF trends (Oesch et al. 2012a, 2013). In that case UDFj-39546284 would be at least $\sim\!20\times$ more luminous. Given the uniform rate of evolution in the UV LF to early times, it is very unlikely that we would find such a luminous galaxy at $z\sim12$.

gestive of a z>10 galaxy. Use of the photometric redshift code ZEBRA (Feldmann et al. 2006) yields a formal redshift estimate of 11.8 ± 0.3 for UDFj-39546284 (Figure 3). We find a similar result with the EAZY photometric redshift code (Brammer et al. 2008). The present estimates are somewhat lower than the Ellis et al. (2013) z=11.9 estimate, likely due to our additional constraint on the luminosity of UDFj-39546284 from the deep K_s -band data.

As in Oesch et al. (2012a) and Ellis et al. (2013), attempts to fit the source with a lower-redshift galaxy SED are not particularly successful. The best low-redshift fit, without a substantial emission-line contribution, is an evolved galaxy at $z_{lowz} = 2.6$. However, the high measured χ^2 value of this fit ($\chi^2_{lowz} = 34.6$) compared to the best-fit solution at z = 11.8 ($\chi^2 = 13.3$) makes this conventional low-redshift solution untenable (but see below).

The new photometry also allows us to set useful constraints on the shape of the spectrum redward of the break. We fit the SED with a power law $f_{\lambda} \propto f_0 \, \lambda^{\beta}$, leaving the redshift, luminosity, and β as free parameters. We find 1σ and 2σ upper limits of -2.3 and -1.5, respectively, for β . These upper limits correspond to the maximum β 's where $\Delta\chi^2 = \chi^2 - \chi^2_{min} = 1$ and 4, respectively. This demonstrates quite definitively that UDFj-39546284 is blue redward of the H_{160} -band and cannot be well fit by an old or dusty low-redshift SED.

3.2. Size and Structural Properties of UDFj-39546284

UDFj-39546284 consists of a compact core, embedded in a more extended structure. The features to the upper left and lower right of the source (Figure 1) appear to extend some $\sim 0.4''$ in radius from the source (see also Ono et al. 2013). Using SExtractor, we measure a half-light radius of ~ 0.17 " for UDFj-39546284 in the deeper

observations. This is larger than the ~ 0.13 "-diameter half-light radius for the PSF. Correcting for the PSF, the half-light radius for this candidate is 0.13".

If we interpret this as a $z\sim12$ source, the implied ~0.5 kpc (physical) half-light radius for the source is consistent with expectations what one would applying a $(1+z)^{-1}$ size scaling to the $z\sim7$ -8 galaxy samples studied by Oesch et al. (2010) where the mean size for comparable-luminosity sources is 0.8 kpc (physical: see also Ono et al. 2013). A $\sim(1+z)^{-1}$ size scaling has been found to describe the evolution of star-forming galaxies over a wide range in redshift (e.g., Buitrago et al. 2008; Oesch et al. 2010). This source is also potentially consistent with expectations if we interpret this as a $z\sim2$ galaxy. The measured half-light radius translates into a physical size of ~1.1 kpc, at the top end of the range expected for extreme emission-line or star-forming galaxies at $z\sim2$ (van der Wel et al. 2012), after correcting for typical $r\propto L^{0.3}$ luminosity dependencies (e.g., de Jong & Lacey 2000).

3.3. Difficulty with $z \sim 12$ Interpretation: Inferred UV Luminosity Is $\sim 20 \times$ Too Large?

While simply identifying UDFj-39546284 as a $z\sim12$ galaxy would seem appropriate (see also Ellis et al. 2013), it becomes problematic when both the apparent UV luminosity of this source and the total search volume in which the source was found are taken into consideration. If the source is at $z\sim12$, its intrinsic luminosity would be $-20.3~(\sim0.5\times$ the luminosity of a $z=3~L^*$ galaxy: Steidel et al. 1999). This is $\sim4\times$ higher than what Bouwens et al. (2011a) and Oesch et al. (2012a) inferred if the source was at $z\sim10.4$ (which seemed plausible before the JH_{140} constraint was available). The much higher luminosity follows from the greater luminosity distance for UDFj-39546284 (factor of ~1.4 change) and the fact that the source is only seen in the reddest one-third of the H_{160} -band (factor of 3 change).

To put this unusually high luminosity in context, we calculate the approximate volume in which we could have found the source. Utilizing the same techniques as in Oesch et al. (2013), we estimate a total search volume of $\sim 3\times 10^3\,\mathrm{Mpc^3}$ (comoving) for UDFj-39546284 in the combined HUDF09/HUDF12/XDF dataset.

The calculated selection volume and observed UV luminosity allow us to derive an approximate LF for star-forming galaxies at z=12, assuming of course that UDFj-39546284 is indeed at z=12. The result is shown in Figure 4 and is unique to this analysis. For context, the LFs inferred for star-forming galaxies at $z\sim4$ -10 from Bouwens et al. (2007), Oesch et al. (2012b), and Oesch et al. (2013) are also presented. It is clear that UDFj-39546284 would be $\sim10\times$ more luminous than similarly-prevalent galaxies at $z\sim10$ and $\sim20\times$ more luminous than similarly-prevalent star-forming galaxies at $z\sim12$, extrapolating lower-redshift LF trends to z>10.

The evolution of the UV LF at early times, i.e., from $z \sim 10$ to $z \sim 4$, is sufficiently uniform that the discovery of a $z \sim 12$ galaxy that is $\sim 20 \times$ more luminous than expected over such a small area is implausible and strongly argues for another explanation.¹¹

¹¹ We remark that gravitational lensing by a foreground source

TABLE 1 Photometry of UDFJ-39546284 and Observations Utilized in Constructing A Deep K_s -band Image of the HUDF09/HUDF12/XDF.

| Photometry of UDFj-39546284 | | K_s -band Observations | | | |
|---|---|---|------------------------------|------------------------------|------------------------------|
| Quantity | Measurement | Instrument | t_{exp} [hrs] | Depth (5σ) | Seeing FWHM ["] |
| RA DEC B_{435} V_{606} i_{775} I_{814} z_{850} Y_{105} J_{125} JH_{140} H_{160} K_s $3.6\mu m$ $4.5\mu m$ $5.8\mu m$ $8.0\mu m$ | $03:32:39.54 \\ -27:46:28.4 \\ -1.0 \pm 1.7 \\ 0.2 \pm 1.1 \\ 1.5 \pm 1.4 \\ -2.9 \pm 3.3 \\ 1.2 \pm 2.5 \\ -0.8 \pm 1.2 \\ -3.9 \pm 1.7 \\ -0.5 \pm 1.6 \\ 11.8 \pm 1.5 \\ (28.7 \pm 0.2 \text{ mag}) \\ -16 \pm 25 \\ 4 \pm 21 \\ 28 \pm 25 \\ -36 \pm 168 \\ -136 \pm 215$ | VLT/HAWK-I VLT/ISAAC PANIC ALL | 28.4 24.2 23.6 76.2 | 26.1 25.8 25.5 26.5 | 0.36 0.35 0.33 0.35 |

NOTE. — Fluxes (corrected to total: §2.2) are given in nJy.

3.4. Emission-Line-Dominated Galaxy?

The properties of UDFj-39546284 are puzzling and difficult to explain as either a low or high-redshift source if the bulk of the H_{160} -band flux is from continuum star light.

However, we can avoid this difficulty if the H_{160} -band light predominantly arises from line emission (see also Ellis et al. 2013). For example, in the lower-middle panel of Figure 3, we show one possible, though somewhat extreme example, where we allow for arbitrary-EW line emission from an AGN. The dust extinction is high (E(B-V)=0.9), and the rest-frame EW of H_{α} is large ($\sim 5000 \text{Å}$). This fit has a $\chi^2 (=17.1)$ more similar to the $z \sim 12$ solution, but for a redshift $z \sim 1.5$. This is adhoc, but demonstrates what is needed.

Support for line emission contributing substantially to the flux in the H_{160} -band comes from the recent analysis of the deep WFC3/IR grism observations of UDFj-39546284 in a companion paper by Brammer et al. (2013). They find evidence of an emission-line feature at 1.6 μ m that could provide most or all of the observed H_{160} -band flux for UDFj-39546284. The existence of such a feature is not unexpected given the difficulty in modelling the source as a pure-continuum galaxy at $z \sim 12$ (because of its luminosity) or $z \sim 2$ -3 ($\chi^2 = 34.6$: Figure 3).

Given the plausiblity of line emission playing a role, the question arises as to the nature of the line emission. Brammer et al. (2013) argue that the emission-line contribution would be from an extreme emission-line galaxy (EELG), notably the [OIII] λ 4959+5007 doublet at $z\sim2.2$. Such galaxies have been found in wide-area grism and imaging surveys with WFC3/IR (van der Wel et al. 2011; Atek et al. 2011; Brammer et al. 2012). Even more extreme examples are needed in the case of UDFj-39546284. Ellis et al. (2013) similarly suggested the source might be an EELG at $z\sim2.4$, but could not

does not seem like a workable explanation for the high luminosity of UDFj-39546284, given the lack of a plausible foreground lens.

explain how such a source could produce the observed spectral break. Brammer et al. (2013) describe the discovery of an EELG at $z\sim1.6$ with an extremely-high [OIII] EW and relatively-red UV colors that would come close to satisfying the constraints if that source were at $z\sim2.2$.

Alternatively the emission-line flux could be from Ly α . EWs of $\sim 200 \,\text{Å}$ are seen in star-forming galaxies in the $z \sim 4$ -6 universe (e.g., Stark et al. 2010) and would cause the source to be brighter by a factor of ~ 4 , resulting in a much more plausible intrinsic luminosity, i.e., $\sim -18.8 \,\mathrm{mag}$. However, even with this luminosity, the source would still be at least $5 \times$ more luminous than one would expect for a comparably-prevalent $z \sim 12$ galaxy (i.e., with the same volume density). Attributing the emission to Ly α also seems implausible given the large amounts of neutral hydrogen expected in the z > 7 universe that would resonantly scatter Ly α photons. Ly α emission is found to be rare in $z \gtrsim 7-8$ galaxies, presumably due to an increasingly neutral IGM (Ono et al. 2012; Schenker et al. 2012; Pentericci et al. 2011; Caruana et al. 2012).

The existence of line emission is a plausible, though not proven, solution to the mystery regarding UDFj-39546284, with the evidence weighted towards a low-redshift solution with an extremely strong [OIII] feature.

4. SUMMARY

We utilize the deeper near-IR observations available over the HUDF09/HUDF12/XDF from the HUDF09, HUDF12 and CANDELS programs to investigate the nature of the $z\sim10$ galaxy candidate UDFj-39546284 (Bouwens et al. 2011a; Oesch et al. 2012a). Using the H_{160} -band observations from the combined HUDF12 and CANDELS programs, we find a 5.3 σ detection at the position of UDFj-39546284, definitively demonstrating that the candidate is real (see also Ellis et al. 2013; Ono et al. 2013). UDFj-39546284 is detected at \sim 7.8 σ in the full 85-orbit H_{160} -band observations.

Making use of deeper ACS+WFC3/IR XDF observations we demonstrate that UDFj-39546284 exhibits a

substantial break in the SED between the H_{160} -band and bluer bands: $\gtrsim 2.2$ mag to the JH_{140} band and $\gtrsim 3.3$ mag to a combined $B_{435}V_{606}i_{775}I_{814}z_{850}Y_{105}J_{125}JH_{140}$ band. Using the deep IRAC and K_s -band observations, we find that UDFj-39546284 has 1σ and 2σ upper limits of -2.3 and -1.5, respectively, for the UV slope β showing quite clearly that UDFj-39546284 is not a red $z \sim 1$ -3 galaxy (Figure 2).

The sharp break in the SED of UDFj-39546284 and blue spectral slope redward of the break is suggestive of a $z \sim 10\text{-}12$ galaxy. The best-fit photometric redshift for UDFj-39546284 using all data, including deep IRAC and K_s -band constraints, is $z = 11.8 \pm 0.3$.

However, interpreting the source as a $z=11.8\pm0.3$ star-forming galaxy is problematic. The UV luminosity inferred for the source if it were at $z\sim12$ is extremely high, $\sim\!20\times$ brighter than expected for similarly-prevalent sources at $z\sim12$ (extrapolating current LF trends).

In light of the uniform evolution seen in the UV LF at early times, it seems implausible that UDFj-39546284 actually corresponds to a $z\sim12$ galaxy unless its H_{160} -

band flux is substantially boosted by Ly α emission. However, this possibility is unlikely given the huge amounts of neutral hydrogen almost certainly present in the $z\sim12$ universe.

Given the tentative detection of an emission line in UDFj-39546284 by Brammer et al. (2013), the most probable interpretation for UDFj-39546284 may be that it corresponds to a rare EELG at $z\sim2.2$ with an observed [OIII] EW >10^4Å. An example of such an EELG is presented by Brammer et al. (2013). Such a high-EW source is even more extreme than other recently-identified EELGs (e.g., van der Wel et al. 2011).

While UDFj-39546284 is not at $z \sim 10$, and probably not at $z \sim 12$, the outcome is comparably interesting, and exemplifies the challenges of exploring the limits of the high-redshift universe with current telescopes as we await JWST.

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REFERENCES

Atek, H., Siana, B., Scarlata, C., et al. 2011, ApJ, 743, 121

Beckwith, S. V. W., et al. 2006, AJ, 132, 1729

Bertin, E. and Arnouts, S. 1996, A&AS, 117, 39

Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2007, ApJ, 670, 928

Bouwens, R. J., Illingworth, G. D., Labbé, I., et al. 2011a, Nature, 469, 504

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011b, ApJ, 737, 90

Bouwens, R., Bradley, L., Zitrin, A., et al. 2013, ApJ, submitted, arXiv:1211.2230

Bradley, L. D., Trenti, M., Oesch, P. A., et al. 2012, ApJ, 760, 108
Brammer, G. B., van Dokkum, P. G., & Coppi, P. 2008, ApJ, 686, 1503

Brammer, G. B., Sánchez-Janssen, R., Labbé, I., et al. 2012a, ApJ, 758, L17

Brammer, G. B., et al. 2013, ApJ, in press, arXiv:1301.0317 Buitrago, F., Trujillo, I., Conselice, C. J., et al. 2008, ApJ, 687, L61

Caruana, J., Bunker, A. J., Wilkins, S. M., et al. 2012, MNRAS, 427, 3055

Coe, D., Zitrin, A., Carrasco, M., et al. 2013, ApJ, 762, 32

de Jong, R. S., & Lacey, C. 2000, ApJ, 545, 781
Ellis, R. S., McLure, R. J., Dunlop, J. S., et al. 2013, ApJ, 763, L7
Fazio, G. G., Hora, J. L., Allen, L. E., et al. 2004, ApJS, 154, 10
Feldmann, R., Carollo, C. M., Porciani, C., et al. 2006, MNRAS, 372, 565

Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, ApJS, 197, 35

Illingworth, G.D., et al. 2013, in preparation

Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, ApJS, 197, 36

Koekemoer, A. M., Ellis, R. S, McLure, R. J., et al. 2013, ApJS, submitted, arXiv:1212.1448

Kron, R. G. 1980, ApJS, 43, 305

Labbé, I., Franx, M., Rudnick, G., et al. 2003, AJ, 125, 1107
 Labbé, I., Bouwens, R., Illingworth, G. D., & Franx, M. 2006, ApJ, 649, L67

Labbé, I., et al. 2010a, ApJ, 708, L26

Labbé, I., et al. 2010b, ApJ, 716, L103

Labbé, I., Oesch, P. A., Bouwens, R. J., et al. 2012, ApJ, submitted, arXiv:1209.3037

Lorenzoni, S., Bunker, A. J., Wilkins, S. M., et al. 2011, MNRAS, 414, 1455

Oesch, P.A., et al. 2010, ApJ, 709, L21

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2012a, ApJ, 745, 110

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2012b, ApJ, 759, 135

Oesch, P. A., Bouwens, R. J., Illingworth, G. D., et al. 2013, ApJ, submitted, arXiv:1301.6162

Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713

Ono, Y., Ouchi, M., Mobasher, B., et al. 2012, ApJ, 744, 83

Ono, Y., Ouchi, M., Curtis-Lake, E., et al. 2013, ApJ, submitted, arXiv:1212.3869

Pentericci, L., Fontana, A., Vanzella, E., et al. 2011, ApJ, 743, 132
Schenker, M. A., Stark, D. P., Ellis, R. S., et al. 2012, ApJ, 744, 179

Stark, D. P., Ellis, R. S., Chiu, K., Ouchi, M., & Bunker, A. 2010, MNRAS, 408, 1628

Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M. and Pettini, M. 1999, ApJ, 519, 1

van der Wel, A., Straughn, A. N., Rix, H.-W., et al. 2011, ApJ, 742, 111

van der Wel, A., Bell, E. F., Häussler, B., et al. 2012, ApJS, 203,

Zheng, W., Postman, M., Zitrin, A., et al. 2012, Nature, 489, 406