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A SEARCH FOR LYMAN BREAK GALAXIES AT $z > 8$ IN THE NICMOS PARALLEL IMAGING SURVEY [1]

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ABSTRACT

We have selected 14 J-dropout Lyman Break Galaxy (LBG) candidates with $J_{110} - H_{160} \geq 2.5$ from the NICMOS Parallel Imaging Survey. This survey consists of 135 square arcminutes of imaging in 228 independent sight lines, reaching average 5σ sensitivities of J_{110} = 25.8 and H_{160} = 25.6 (AB). Distinguishing these candidates from dust reddened star forming galaxies at $z \sim 2-3$ is difficult, and will require longer wavelength observations. We consider the likelihood that any J-dropout LBGs exist in this survey, and find that if $L^*_{z=9.5}$ is significantly brighter than $L^*_{z=6}$ (a factor of four), then a few J-dropout LBGs are likely. A similar increase in luminosity has been suggested by Eyles et al. and Yan et al., but the magnitude of this increase is uncertain.

Subject headings: galaxies: high-redshift – galaxies: evolution – galaxies: formation

1. INTRODUCTION

Searches for Lyman break galaxies (LBGs) have measured their luminosity functions out to high redshifts ($z = 4-5$; Kashikawa et al. 2006; Yoshida et al. 2006). This indicates that substantial numbers of galaxies were in place at z=6, and that galaxy formation must be ongoing at higher redshifts. Yan et al. (2006) and Eyles et al. (2006) have shown that the existing mass in *i*-dropouts at $z = 6$ can not be assembled unless star formation rates were higher in the past. The implied rapid first bursts of star formation at $z > 7$ could produce galaxies with large enough rest-wavelength UV luminosities to be detected in the near infrared. In addition, it is currently uncertain if the the amount of star formation at $z = 6$ is adequate to reionize the universe. J-dropout LBGs may play an important role in this process, which is likely between $9 \leq z \leq 14$ (Spergel et al. 2006).

The NICMOS Parallel Imaging Survey (Henry et al. 2005; Henry et al. in prep), provides the unique combination of sensitivity and wide area coverage required to find rare, luminous LBGs with $8 \leq z \leq 11$. With 135 arcminutes^2 in 228 independent sight lines, we cover an order of magnitude more sky than the NICMOS portions of Hubble Deep Field North (HDF-N; Dickinson 1999; Thompson et al. 1999) and the Ultra Deep Field (UDF; Thompson et al. 2005). Although the NICMOS Parallel Imaging Survey is less sensitive than these surveys, the galaxies presented here are better suited for follow-up observations. In addition, it surpasses most ground based imaging.

We have identified a sample of possible J-dropout galaxies from the NICMOS Parallel Survey, and here we discuss the likelihood that any of them are at $z \geq 8$, as well as the possible implications for star formation near the epoch of reionization. We use H_o = 71 km s^{-1} Mpc^{-1}, Ω_Λ = 0.73, and Ω_M = 0.27, and AB magnitudes are used throughout. We take $M^*_{1500}(z = 3)$ = –21.1 (Steidel et al. 1999), which corresponds to H_{160} = 26.4 at z = 9.5.

2. OBSERVATIONS & SOURCE SELECTION

2.1. *The NICMOS Parallel Survey*

We conducted the NICMOS Parallel Survey in *Hubble Space Telescope* (HST) observing cycles 7, 11, 12, and 13. Images and slitless grism spectroscopy were obtained in the parallel mode, using the NICMOS 3 camera (Thompson et al. 1998). Early results from the cycle 7 survey are presented in McCarthy et al. (1999), Yan et al. (1998, 1999, 2000), and Teplitz et al. (1998).

The cycles 11, 12, and 13 imaging data will be described in more detail in Henry et al. (in prep); we provide a summary here. Each field was observed with both the J_{110} ($F110W$) and H_{160} ($F160W$) filters, with average integration times of $\sim$1500 s and $\sim$2000 s. Images are drizzled according to Fruchter & Hook (1997), and the resulting point spread function has a FWHM $\sim 0.3''$. Photometry was performed with SExtractor (Bertin & Arnouts 1996) in dual image mode. The H_{160} images were used to detect sources, and fluxes were measured from identical Kron (1980) apertures in both bands. We require 9 pixels above 1.5σ for detection. We further require a 5σ detection in H_{160}, as measured in a $0''.8$ diameter aperture. The average 5σ sensitivities reached are J_{110} = 25.8 and H_{160} = 25.6. We detect 7700 objects; the color magnitude diagram is shown in Figure 1 (left).

2.2. *J-dropout candidates*

In Figure 1 (right) we show Bruzual & Charlot (2003) evolutionary tracks to which we have added an IGM foreground absorption component which is completely opaque beyond $z = 6$, where Lyα passes into the J_{110} filter. In addition, we show examples of two local ultra-luminous infrared galaxies (ULIRGs), Arp 220, and IRAS 03521+0028. For Arp 220 we compile the UV to near infrared spectral energy distribution (SED) from Goldader et al. (2002), Surace et al. (2000), and the RC3 catalog. For IRAS 03521+0028, which has a very red rest frame optical SED, only the BIHK' photometry from Surace et al. (2000) is available, so we do not extend this track beyond $z = 2$.

[1] Based on observations made with the NASA/ESA *Hubble Space Telescope*, obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy Inc., under NASA contract NAS 5-26555. These observations are associated with proposals 9484, 9865, and 10226.

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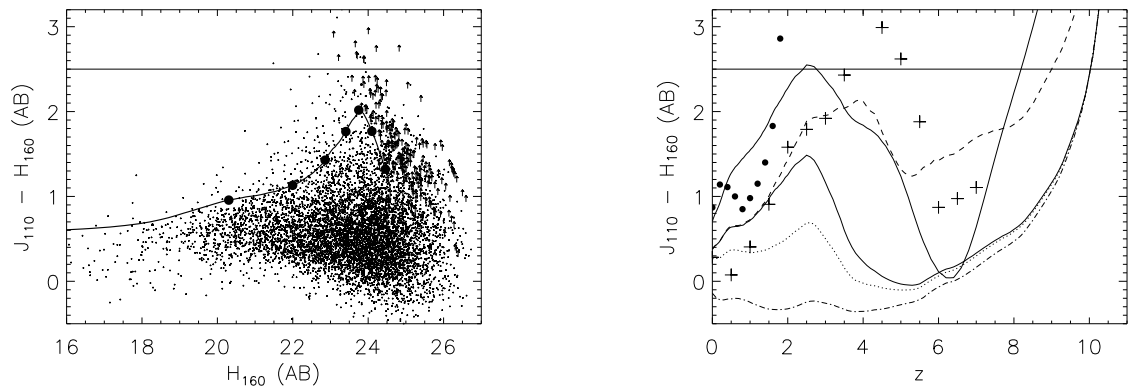

FIG. 1.— *Left* – The NICMOS Parallels Imaging Survey color magnitude diagram. All points are 5σ detections, or better, in H_{160}. Arrows represent sources with no J_{110} detection above 3σ. We overplot the Bruzual & Charlot (2003) evolutionary track of a galaxy which formed at z_f = 12, with a A_V = 1, a Salpeter IMF, solar metallicty, and an exponentially declining star formation rate with a 500 Myr e-folding time. This model galaxy has a stellar mass of $7 \times 10^{10} M_\odot$ at z = 0. The track is marked with fiducial redshift points at $z = 0.5, 1.0, 1.5, 2.0, 2.5$ (peak), $3.0, 3.5$. *Right* –Curves show Bruzual & Charlot (2003) evolutionary tracks. All models have a Salpeter initial mass function and solar metallicity. The bluest, dot-dashed track is a 10 Myr old model with constant star formation and no extinction, while the remaining tracks are evolving, with z_f = 12. Their star formation histories and extinctions are: *dotted*– Constant with 10 $M_\odot$ yr^{-1}, and A_V = 0; *solid*– Exponentially declining, with a 0.5 Gyr e-folding time, and A_V = 0 and 2; *dashed*– An instantaneous burst with A_V = 0. Extinction is added following the prescription by Cardelli et al. (1989), which contains a 2000Å bump. At $z \sim 6$ this feature is in the H_{160} filter, the resulting dust obscured color is *bluer* than the intrinsic color. We also show the expected colors from two local ULIRG SEDs, Arp 220 (crosses), and IRAS 03521+0028 (points). The horizontal line indicates the color cut which we made at $J_{110} - H_{160} \geq 2.5$.

To minimize contamination from lower redshift interlopers, we adopt the color selection $J_{110} - H_{160} > 2.5$ for J-dropout candidates. Figure 1 (right) shows that the reddest J-dropout LBGs will be selected at $z \gtrsim 8$, while nearly all models meet this criterion at $z > 10$. We find 14 J-dropout candidates (Table 1); five are detected in J_{110} (at 3σ or better), but this does not disqualify them as LBGs, since some flux will fall in the J_{110} filter for $z < 10.5$. The remaining nine galaxies are among the sources which are plotted as lower limits (upward pointing arrows) in Figure 1. Possible contamination from lower redshift sources is discussed in §3.1.

Since exposure times varied from field to field, the NICMOS Parallel Survey is inhomogeneous in sensitivity. For selection of red galaxies, the faint limit of the sample is determined by the sensitivity in the J_{110} images. For example, at H_{160} = 23.3, 98% of the J_{110} images have sufficient sensitivity for sources to be selected with $J_{110} - H_{160} \geq 2.5$. A half magnitude fainter, at H_{160} = 23.8, this completeness drops to $\sim$ 50%. Since fainter galaxies are more likely to be genuine J-dropout LBGs, we consider all galaxies with $J_{110} - H_{160} \geq 2.5$, and correct for this incompleteness.

3. DISCUSSION

3.1. *Foreground Contamination*

Figure 1 (right) shows that some lower redshift galaxies may be selected as J-dropout candidates. Bouwens et al. (2005) find three galaxies with $J_{110} - H_{160} \geq 2.5$ in a 15 arcmin^2 survey. This density is consistent with the 14 sources we have found, since the NICMOS Parallel Imaging Survey covers ten times the area of Bouwens et al., although with less sensitivity. Bouwens et al. use optical and K-band photometry to argue that these galaxies are all at lower redshift. Since they find no J-dropout LBGs with $J_{110} - H_{160} \geq 2.5$, the implied density is less than 250 degree^{-2}.

In addition, we consider the SEDs of two local ULIRGs. Daddi et al. (2005) have shown that ULIRGs have a surface density of about 1 arcmin^{-2} at $z = 2-3$. For Arp 220 ($L_{bol} = 1.5 \times 10^{12} L_\odot$), we expect H_{160} = 23.6 at z = 2, which is typical of the galaxies in this survey. However, ULIRGs like Arp 220 are not red enough at $z = 2-3$ to be selected as part of this sample. In Figure 1 (right) we show the predicted color of another ULIRG, IRAS 03521+0028, which has a very red rest frame optical SED. This galaxy is red enough to be selected at z = 2, but it is doubtful if many ULIRGs at $z = 2-3$ can be described by this red optical SED. If $\sim$10% display similar colors, this could account for the 14 J-dropout candidates. While galaxies like Arp 220 could also be selected by our color cut at $z \sim 4-5$, ULIRGS at these redshifts are expected to be rare, and would have to be very luminous, with $L_{bol} \gtrsim \times 10^{13} L_\odot$. Even at $z = 2-3$, the density of ULIRGs of this luminosity is low, with only $\sim$ 15 degree^{-2} (L. Yan et al. 2005).

Contamination from Galactic sources is improbable. Dickinson et al. (2000) report on a similar point source in the HDF-N, with $J_{110} - H_{160} > 2.3$, and find that it is unlikely a stellar or substellar source.

3.2. *Estimating the Density of Galaxies at $z \geq 8$*

Since no objects have ever been confirmed at less than 500 Myrs after the Big Bang, it is difficult to predict how bright or numerous they will be. Since small uncertainties in $L^*_{z=9.5}$ can have a large effect, we consider both a Schecter luminosity function (LF), and a broken power law of the form:

$$\phi(m) = \frac{\phi^*}{10^{0.4(\alpha_1+1)(m-m^*)} + 10^{0.4(\alpha_2+1)(m-m^*)}} \qquad (1)$$

with faint end slope α_1 and luminous slope α_2[1]. In Figure 2, we show contours in surface density, calculated by integrating the luminosity function for a range of plausible ϕ^* and $H^*(z = 9.5)$:

$$N = \int_z dz \frac{dV}{dz} \int_m P(m,z)\phi(m, m^*(z))dm. \qquad (2)$$

[1] We fit the above broken power law to the z = 3 population from Steidel et al. (1999), and the z = 6 LBGs from Bouwens et al. (2006). We find $\alpha_2 \sim -4$, and $\alpha_1 \sim -1.6$ in both populations, so we hold both slopes constant.

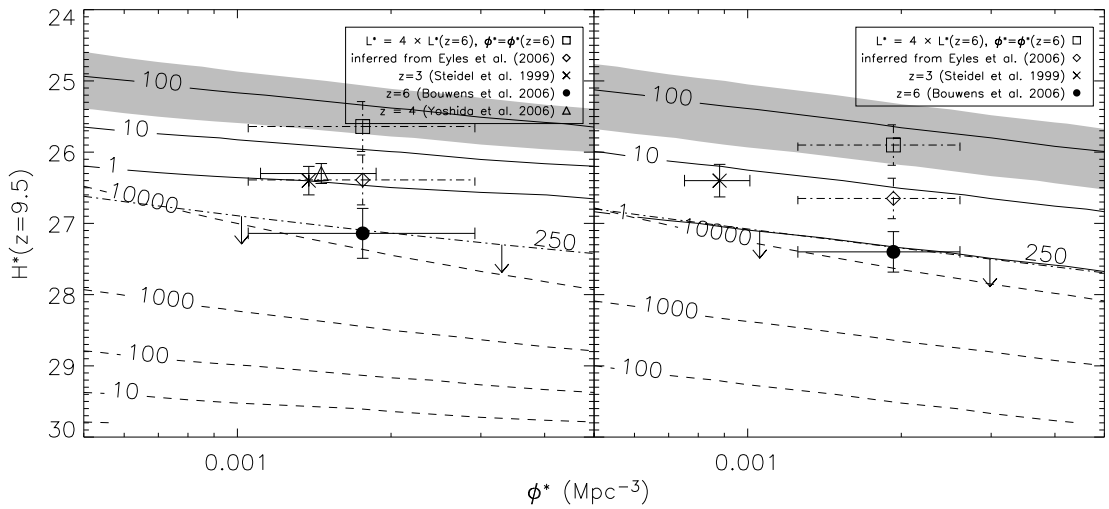

FIG. 2.— Contours of galaxies per square degree for this survey (solid) and a survey which is complete to 28.0 (dashed), calculated using a Schecter luminosity function (left), and a broken power law with the high-L slope fixed at -4 (right). The grey region indicates 1-10 objects in this 135 square arcminute survey. The dot-dashed curve indicates $\lesssim 250$ degree^{-2} in the Bouwens et al. (2005) search for J-dropout LBGs. In the right panel, the dot-dashed curve overlaps the solid contour for 1 degree^{-2}. The points indicate estimates of the LF at z=9.5, from lower redshift populations.

This allows for the dimming of H^*_{160} with redshift, which is large for $z > 10.5$, where the Lyα absorption passes into the H_{160} filter. The quantity $dz\frac{dV}{dz}$ is the comoving volume element, and $P(m,z)$ corrects for galaxies which are missed because of incompleteness, or because they are not red enough to be selected by our color cut. To estimate $P(m,z)$, we separate the quantity into $P(m,z) = p_1(m)p_2(z)$, taking $p_1(m)$ as the completeness which we discussed in §2.2. For $p_2(z)$, we assume that galaxies are equally distributed between the reddest and bluest models in Figure 1 (right)[2], so that $p_2(z)$ increases from zero to one between $8 < z < 10$. Under these assumptions, the galaxies in this survey should lie between $8 \leq z \leq 11$, with an average redshift of between $z = 9-10$, depending on the chosen LF. We therefore adopt an average redshift of $z = 9.5$. We repeat this calculation to estimate a constraint on the LF based on the upper limit in surface density found in the Bouwens et al. (2005) search for J-dropouts, which consists of six fields imaged to an average sensitivity of $H_{160} = 28.0$. Like the NICMOS Parallel Survey, the Bouwens et al. (2005) survey is limited by sensitivity in J_{110}, so that galaxies with $J_{110} - H_{160} \geq 2.5$ are only selected down to $H_{160} \sim 25.5$. Their finding of less than 250 degree^{-2} is plotted as the dot-dashed line in Figure 2. Also, for comparison to more sensitive surveys, we show surface densities calculated with $p_1(m) = 1$ and a detection limit of $H_{160} = 28$ (This requires a sensitivity of $J_{110} = 30.5$, which can be reached in less than 10 hours of integration with the *James Webb Space Telescope*).

These plots show the expected density of J-dropout LBGs, based on a given H^* and ϕ^*. The shaded area of Figure 2 shows the allowed region for H^* and ϕ^* if 1-10 J-dropout LBGs exist in this survey. If none of the candidates are $z \geq 8$ LBGs, then H^* and ϕ^* should be below the shaded region. We show examples from a few observed LFs, including the broken power law fits which we made. If the $z = 6$ measurement by Bouwens et al. (2006) is a good indicator of the population at $z \sim 9.5$, then the density of sources which we expect is of order 0.01 degree^{-2} in the Schecter form, and about 1 degree^{-2} in the broken power law LF. These densities are too low to suggest any J-dropout LBGs in the NICMOS Parallel Survey, which covers only 0.04 degree^2. On the other hand, Richard et al. (2006), in a lensing survey for J-dropout galaxies, find that the $z = 8-10$ LF may be more like the $z = 3$ LF by Steidel et al. (1999). In this case, the chances of finding a J-dropout LBG in the NICMOS Parallel Survey are better, with about 1-10 degree^{-2} in both the Schecter and broken power law forms.

The LF constraint which we estimated from the absence of J-dropout galaxies with $J_{110} - H_{160} \geq 2.5$ in the Bouwens et al. (2005) survey suggests they are too few and too faint for any to be found in the NICMOS Parallel Survey. However, Bouwens et al. survey only a small volume for rare objects, and so the cosmic variance will be large. Alternatively, the results of Yan et al. (2006) and Eyles et al. (2006) show that to produce the observed mass density at $z = 6$, the progenitors at $z > 7$ must have formed stars more rapidly in the past. The magnitude of this brightening is uncertain, but Eyles et al. (2006) suggest it is a factor of a few. We show this inferred LF, as two times brighter than the $z = 6$ measurement by Bouwens et al. (2006), with no density evolution. This predicted LF is similar to the measurement by Richard et al. (2006), again, suggesting that we expect, at best, a 40% chance of finding a J-dropout LBG. If the brightening in the LF is instead a factor of four larger than at $z = 6$, then we can expect one or two J-dropout LBGs. In addition, we find that more than a factor of ten increase in L^* (with no density evolution) is unlikely, since we would then expect more than 16 galaxies with $J_{110} - H_{160} \geq 2.5$ in this survey.

3.3. *Star Formation & Reionization at $z \geq 8$*

J-dropout galaxies may play an important role in the reionization of the universe. The critical star formation rate density (ρ_{SFR}) required to ionize the universe, is $\rho_{SFR}(z = 9.5) = 0.09\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$ (Madau et al. 1999), if all ionizing photons escape the galaxies, and the clumping factor of ionized

[2] This is consistent with the results of Thompson (2003) and Thompson et al. (2006), which find that high redshift galaxies are best fit by the bluest spectral types. Even the reddest model used here is only a few hundred Myrs old at $z = 8$ and is therefore comparable to the blue models used by Thompson et al.

TABLE 1
J-DROPOUT LBG CANDIDATES WITH $J_{110} - H_{160} > 2.5$.

ID	H_{160}	H_{160} S/N	$J_{110} - H_{160}$ (AB)	RA (J2000)	Dec(J2000)	FWHM ($''$)
1	24.8	36	> 2.7	14 46 16.09	40 30 10.9	0.32
2	23.2	26	> 2.6	22 15 11.95	-14 08 01.0	0.55
3	23.9	26	> 2.6	02 05 29.41	-12 05 55.1	0.39
4	24.2	35	> 2.7	02 31 17.39	-08 49 17.5	0.30
5	23.3	50	3.2	00 59 36.34	-51 13 55.5	0.44
6	23.9	30	> 2.6	07 44 21.68	39 21 41.1	0.42
7	23.7	37	> 2.8	09 48 39.80	67 30 23.7	0.32
8	24.0	43	> 2.9	10 47 44.77	13 46 58.1	0.46
9	23.9	28	2.6	15 34 13.04	26 48 24.3	0.36
10	23.2	48	3.1	12 35 42.37	62 10 30.4	0.38
11	22.7	51	2.7	02 09 57.31	-50 55 29.2	1.47
12	23.7	27	> 2.6	21 03 57.60	03 16 28.2	0.37
13	23.8	30	2.6	17 58 07.12	66 45 19.9	0.49
14	23.1	33	> 2.8	00 25 42.99	-12 25 29.2	0.39

hydrogen is 30. These parameters are uncertain, but this is much larger than the upper limit posed by Bouwens et al. (2005) for galaxies at $z \sim 10$. Alternatively, for the LF which predicts a few J-dropout LBGs in this survey, where $L^*_{z=9.5} = 4 \times L^*_{z=6}$, and $\phi^*_{z=9.5} = \phi^*_{z=6}$, we calculate $\rho_{SFR}(z = 9.5) \sim 0.1\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$ in both the Schecter and broken power law forms. In this case, J-dropout LBGs may be capable of reionizing the universe, although the uncertainties in the escape fraction of ionizing photons, and the clumping factor of ionized hydrogen must be addressed.

To conclude, it is not implausible that ρ_{SFR} is very large during the first few hundred million years of galaxy formation if stars were formed in rapid bursts. In fact, cofirmation of any J-dropout galaxies will suggest a large ρ_{SFR} for most reasonable $H^*(z = 9.5)$. Follow-up observations of the galaxies presented here is one way to constrain star formation at $z \geq 8$.

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