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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 $5\sigma$ 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-drops 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 arcminutes2 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$^{-1}$, $\Omega_m = 0.73$, and $\Omega_k = 0.27$, 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 $1.5\sigma$ for detection. We further require a $5\sigma$ detection in $H_{160}$, as measured in a $0''/8$ diameter aperture. The average $5\sigma$ sensitivities reached are $J_{110} = 25.8$ and $H_{160} = 25.6$. We detect 7700 objects; the color magnitude distribution 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 Ly$\alpha$ 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 $z = 2$.  

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covers ten times the area of Bouwens et al., although with

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arcmin

and correct for this incompleteness.

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 2 (right) we show the predicted 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 $z \geq 8$, while nearly all models meet this criterion at $z > 10$. We find 14 J-dropout candidates (Table A), five are detected in $J_{110}$ (at 3$\sigma$ 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 §3.2.

Since exposure times varied from field to field, the NICMOS Parallel Imaging 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$^{-2}$.

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LBGs exist in this survey. If none of the candidates are hundred Myrs old at by the bluest spectral types. Even the reddest model used here is only a few broken power law fits which we made. If the We show examples from a few observed LFs, including the requires a sensitivity of to more sensitive surveys, we show surface densities calcu-
ment, and based on a given Telescope James Webb Space less than 10 hours of integration with the
This allows for the dimming of $H_{160}$ with redshift, which is large for $z > 10.5$, where the Ly absorption passes into the $H_{160}$ filter. The quantity $dz_H$ 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 $\phi^*$. The shaded area of Figure 2 shows the allowed region for $H^*$ and $\phi^*$ if 1-10 J-dropout LBGs exist in this survey. If none of the candidates are $z \geq 8$ LBGs, then $H^*$ and $\phi^*$ 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 ($\dot{\rho}_{\text{SFR}}$) required to ionize the universe, is $\dot{\rho}_{\text{SFR}}(z = 9.5) = 0.09 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3}$ (Madau et al. 1999), if all ionizing photons escape the galaxies, and the clumping factor of ionized

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$^2$ This is consistent with the results of Thompson et al. (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.
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 \( L^{*}_{\text{phot}} = 4 \times L^{*}_{\text{H} \delta} \) and \( \phi^{*}_{\text{phot}} = \phi^{*}_{\text{H} \delta} \), we calculate \( \rho_{\text{SFR}}(z=9.5) \sim 0.1 \ M_{\odot} \ yr^{-1} \ Mpc^{-3} \) 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 \( \rho_{\text{SFR}} \) is very large during the first few hundred million years of galaxy formation if stars were formed in rapid bursts. In fact, confirmation of any J-dropout galaxies will suggest a large \( \rho_{\text{SFR}} \) 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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REFERENCES

Henry, A. L., Colbert, J. W., Malkan, M. A., McCarthy, P. J., Teplitz, H. I., & Yan, L. 2005, BAAS, 37, 1194


TABLE 1

J-DROPOUT LBG CANDIDATES WITH \( J_{110}-H_{160} > 2.5 \).

<table>
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