NEW RESULTS FROM THE MAGELLAN IMACS SPECTROSCOPIC Lyα SURVEY: NICMOS OBSERVATIONS OF Lyα EMITTERS AT $z = 5.7^*$

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ABSTRACT

We present NICMOS $J_{110}$ (rest-frame 1200–2100 Å) observations of the three $z = 5.7$ Lyα emitters discovered in the blind multislit spectroscopic survey by Martin et al. These images confirm the presence of the two sources that were previously only seen in spectroscopic observations. The third source, which is undetected in our $J_{110}$ observations, has been detected in narrowband imaging of the Cosmic Origins Survey, so our non-detection implies a rest-frame equivalent width $>146$ Å (3σ). The two $J_{110}$-detected sources have monoprest-frame equivalent widths of 30–40 Å, but all three are typical of high-redshift Lyα emitters. In addition, the $J_{110}$-detected sources have UV luminosities that are within a factor of 2 of $L_{UV}$, and sizes that appear compact ($r_{90} \sim 0.1$5) in our NIC2 images—consistent with a redshift of 5.7. We use these UV-continuum and Lyα measurements to estimate the $i_{775}-z_{850}$ colors of these galaxies and show that at least one and possibly all three would be missed by the i-dropout Lyman break galaxy selection. These observations help demonstrate the utility of multislit narrowband spectroscopy as a technique for finding faint emission-line galaxies.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

1. INTRODUCTION

Studying the epoch around $z \sim 6$ is important for our understanding of the early stages of galaxy formation. It is around this time, when the age of the universe was less than a Gyr, that the reionization of the hydrogen component of the intergalactic medium (IGM) was substantially completed (Fan et al. 2006). Hundreds of $z \sim 6$ galaxies have now been photometrically selected (e.g., Bouwens et al. 2007; McLure et al. 2009), and at least tens of Lyman break galaxies (LBGs) and many more Lyα emitters (LAEs) are now spectroscopically confirmed (Dow-Hygvelund et al. 2007; Vanzella et al. 2009; Stanway et al. 2007; Kashikawa et al. 2006; Shimazu et al. 2006; Stark et al. 2010). While there are hints of substantial star formation at even higher redshifts (Eyles et al. 2005, 2007; Yan et al. 2006; Simcoe 2006; Ryan-Weber et al. 2009; Dunkley et al. 2009; Bouwens et al. 2008, 2010; Bunker et al. 2009), $z \sim 6$ remains the earliest epoch for which robust galaxy samples are available.

At $z \sim 6$, galaxies are selected via the Lyman break method (Meier 1976; Steidel et al. 1996) or because of strong Lyα emission (Hu et al. 2002, 2004; Rhoads et al. 2004; Ajiki et al. 2004; Westra et al. 2006). Both methods select star-forming galaxies, but the two populations differ. Not all LBGs have Lyα emission (Shapley et al. 2003; Stanway et al. 2007; Vanzella et al. 2009) and LAEs can be missed by LBG surveys because they are faint in the continuum or their Lyα emission contaminates broadband photometry. Studies of LAEs are an important complement to LBG surveys, because the faint continuum luminosities and high specific star formation rates (SFRs) of LAEs make them likely candidates for galaxy building blocks.

To date, narrowband imaging surveys have been very successful in finding LAEs at $z \sim 3–6$. Multiwavelength observations have shown that these LAEs are typically (but not always) younger and less massive, and they have lower dust extinction than LBGs (Finkelstein et al. 2007, 2008, 2009; Gawiser et al. 2006, 2007; Nilsson et al. 2007; Lai et al. 2008; Kornei et al. 2010). In addition, Lyα luminosity functions (LFs) measured at $z \sim 3–6$ show little or no evolution with redshift (Shimasaku et al. 2006; Gronwall et al. 2007; Dawson et al. 2007; Murayama et al. 2007; Ouchi et al. 2008). At higher redshifts, measurements of the Lyα LF may allow a determination of the neutral hydrogen fraction in the IGM and LAE clustering could help constrain models of the pathiness of the reionization process (Santos 2004; Santos et al. 2004; Haiman & Cen 2005; Furlanetto et al. 2006; Dijkstra et al. 2007; McQuinn et al. 2007). In fact, Kashikawa et al. (2006) now report a measured decline in the Lyα LF at $z = 6.5$, although this is not seen in a compilation of different data sets presented by Malhotra & Rhoads (2004).

Spectroscopic searches for LAEs have the potential to detect objects with fainter line emission than purely narrowband imaging, because they sample with a resolution closer to the intrinsic width of the emission line. This is especially important at $z \gtrsim 6$, where observing the faint end of the galaxy LF is challenging. However, the task is challenging and first efforts at blank sky surveys using multislit narrowband spectroscopy at Keck Observatory and the Very Large Telescope (VLT) found only low- and intermediate-redshift interlopers (Tran et al. 2004; Martin & Sawicki 2004). More recently, different spectroscopic strategies have met success. Sawicki et al. (2008) have found several faint serendipitous LAEs at $z = 4.4–4.9$ in a search of 20% of the DEEP2 database. While the area subtended by DEEP2 slits is only 21.6 arcmin$^2$, a large line-of-sight volume is sampled within the relatively OH-free portion of the sky spectrum at $\lambda < 7000$ Å. In addition, Rauch et al. (2008) found 27 $z \sim 3$ LAEs in a single longslit spectrum; their $\sim 100$ hr VLT observation reached a flux $1–2$ orders of magnitude.
magnitude deeper than most other LAE searches. At higher redshifts, slitless spectroscopy with the Hubble Space Telescope (HST) has uncovered a few sources at \( z > 5 \) (Pizolkal et al. 2007), and longslit spectroscopy of the critical lines of strong gravitational lenses has discovered low-luminosity LAEs at \( z \sim 6 \) (Santos et al. 2004), as well as a few candidates at \( z > 8 \) (Stark et al. 2007).

Recently, wider areas have become accessible with multiplex narrowband spectroscopy, and LAEs have been found at \( z \approx 5.7 \). Using the Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2006), Martin et al. (2008) carried out a blind spectroscopic search in 200 arcmin \(^2\) in the H \( \alpha \) islit narrowband spectroscopy, and LAEs have been found \( z > 8 \) (Stark et al. 2007). Sensitivity was measured by randomly placing 0.6 diameter apertures in the image, rejecting those that fell on sources and fitting a Gaussian to the “counts-per-aperture” distribution, as described in Henry et al. (2009). We found a 5\( \sigma \) sensitivity of \( J_{110} = 26.5 \) in this aperture. Using the point sources in our images, we measured the aperture correction to be 0.08 mag, so the 5\( \sigma \) total sensitivity is \( J_{110} = 26.4 \) (for a point source). Finally, using a few common sources per image, the astrometric solutions to the NICMOS images were aligned with the COSMOS survey for the 10 hr field, and the Sloan Digital Sky Survey for the 15 hr field.

2. Observations and Data Reduction

2.1. NICMOS Imaging

Each of the three LAEs was observed for five orbits (13.4 ks) with the NICMOS 2 camera. The images were then processed in several steps to make final mosaics. First, images were corrected for the quadrant-dependent variable bias (“pedestal effect”), and South Atlantic Anomaly darks were subtracted with the NIC2 camera. The images were then processed with the NICMOS Imaging and Multi-Object Spectrometer (NICMOS; Thompson et al. 1998). These images, obtained through the \( J_{110} \) filter with the NIC2 camera, confirm the presence of the two LAEs in the 15 hr field. In Section 2, we present our observations and data reduction, as well as the process by which we match our spectroscopically discovered sources with NICMOS detections. In Section 3, we discuss the properties of these three LAEs and Section 4 contains a summary of our results. We use \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.7 \), \( \Omega_\Lambda = 0.3 \), and AB magnitudes throughout.

This image was shifted back to the frame of the original input image, and pixels deviant by more than 3\( \sigma \) were flagged as bad pixels. Finally, images were combined with drizzle with bad pixels masked using parameters recommended in the Dither Handbook: pixfrac = 0.6 and scale = 0.5. The final output pixels are 0.038.

The resulting point-spread function (PSF), measured from the two point sources in these images, has an FWHM of 0.1.

The spectroscopic search and confirmation data are presented in Martin et al. (2008), where a difference was discovered between the World Coordinate System (WCS) zero points of COSMOS and that of our data. Namely, the position of MSDM 80+3 in the COSMOS/Subaru narrowband imaging is nearly 1 arcsec west of the position found by Martin et al. In light of this offset, we improved our technique for deriving coordinates, by mapping a WCS solution to images taken through our slitmask. We tested these solutions for both the COSMOS and 15 hr field, using dozens of objects (per field) that have continuum detections in our spectra. We found (1\( \sigma \)) position uncertainties of 0.3–0.5 along the slits and 1″ perpendicular to the slits. The latter uncertainty naturally arises in all blind spectroscopic searches, because sources are not necessarily centered in the slits. For the COSMOS field, the slits are oriented east–west, so these uncertainties correspond to R.A. and decl., respectively. For the 15 hr field, the slit position angle (P.A.) was −45°.

In Figure 1, we show the NICMOS \( J_{110} \) images at the positions of the three LAEs. No obvious source is detected at the position of MSDM 80+3, but sources are detected within the 1σ position error ellipse for MSDM 29.5+5 and just outside it for MSDM 71–5. Photometry is presented in Table 1. We used 0.6 diameter apertures, centered on the positions of the sources shown in Figure 1 for MSDM 29.5+5 and MSDM 71–5, and at the position of the narrowband detection for MSDM 80+3 (see Figure 2). A point-source model was adopted for the aperture correction, as explained in Section 2.1. While more light will be missed from extended sources, this loss amounts to at most 0.1–0.3 mag (in addition to the point-source aperture correction), as nearly all \( z \sim 6 \) galaxies have half-light radii, \( r_{1/2} < 0.2 \) (Bouwens et al. 2004; Ferguson et al. 2004). As we cannot accurately determine the amount of missed flux, we adopt the point-source aperture correction of 0.1 mag and note this systematic uncertainty.

In order to determine whether the sources are likely to be associated with the LAEs, we calculated the probability that the NICMOS detections in the 15 hr field are from foreground galaxies. To do this, we obtained the publicly available catalogs of the NICMOS Ultra-Deep Field (UDF4; Thompson et al. 2005). For consistency with our aperture...

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4 http://archive.stsci.edu/prepds/udf/udf_hsp.html
of the two detected sources, we found cumulative number counts photometry and equivalent width measurements. This enhancement. photometry of the LAEs, we used 0.6” diameter apertures. To $J_{110} = 26.1$, which is the aperture magnitude of the fainter of the two detected sources, we found cumulative number counts of ~60 arcmin$^{-2}$. Therefore, there is less than a 1% chance of a foreground interloper falling within our positional error ellipse. For the brighter source, this probability is about 50% lower. We conclude with greater than 99% confidence that each of the NICMOS-detected sources is indeed an LAE discovered by Martin et al. (2008).

2.3. Lyα Contribution to Broadband Photometry?

Strong Lyα emission can, in some cases, contribute appreciably to broadband flux density (Schaerer & de Barros 2010), and for our objects this could happen. At $z = 5.7$, Lyα is included in the wide $J_{110}$ bandpass, which covers approximately 8000 Å to 1.4 μm. However, the contribution is negligible for our objects—our measured Lyα fluxes account for only 5%–10% of the $J_{110}$ flux densities for the two detected sources. This enhancement lies within our uncertainties, so no corrections are made to our photometry and equivalent width measurements.

3. DISCUSSION

3.1. MSDM 80+3: Comparison to Narrowband Observations

These NICMOS observations provide the first direct images of two sources (MSDM 29.5+5 and MSDM 71–5) which had previously only been detected in our spectroscopic data. On the other hand, the source which is undetected in $J_{110}$, MSDM 80+3, shows a strong detection in Subaru narrowband imaging with the NB816 filter (object 55 in Murayama et al. 2007). In Figure 2, we show the narrowband image of MSDM 80+3, with our position error ellipse overlaid. Our improved coordinates for MSDM 80+3 are roughly consistent with the NB816 source in Murayama et al. The newly derived position is 0.7 west of the NB816 detection, while the previous position given in Martin et al. was 1” east. This position offset along the slit is still large compared to other sources, including those discussed in Section 2.2 and for 52 lower redshift line emitters that are in common between Martin et al. and the COSMOS NB816 sample. Given the slight offset perpendicular to the slit (0.4”) shown in Figure 2, one possibility is that the Lyα emission from this object is extended, and our slit subtended an outlying region of the galaxy. Some evidence for this hypothesis is present in...
the Subaru narrowband image (Figure 2), where MSDM 80+3 is marginally resolved.

The absence of continuum emission could indicate that the source is extended in the continuum, although extended Ly_{α} emission need not imply a similarly extended stellar continuum. The upper bound of i-dropout LBG sizes is r_{90} < 0.2′ (in the rest-frame UV; Bouwens et al. 2004), which corresponds to 5.3 pixels in our drizzled NIC2 images. Using the IRAF artdata package, we verified that a galaxy of this size would be undetected in our NICMOS data at J_{110} > 26.5. It is tempting to conclude from the low-surface brightness signal at the position of MSDM 80+3 in our NICMOS image that it may be more extended in the rest-frame UV. However, this LAE fell on the bad central column in these observations, and similar artifacts appear at other locations along the column. The weight maps produced by drizzle indicate that noise is ~30% higher at these locations relative to the rest of the image, so the extended feature is not significant. Nevertheless, the J_{110} non-detection could imply that MSDM 80+3 is more extended in the continuum than the other two LAEs (MSDM 29.5+5 and 71−5), which have half-light radii (measured with SExtractor) of 0.15′ and 0.14′.

The hypothesis that the Ly_{α} emission may be extended is also supported by our line flux measurement, which is a factor of 2 lower than the Subaru NB816 imaged line flux. This difference is larger than is expected for a point source, unless the object fell on the edge of our 1′.5-wide slit. As noted above, in the narrowband image coordinates, MSDM 80+3 is 0.4′ north of the slit center. Using the point-source slit loss models from Martin et al. (2008) at this position, we expect only about a 20% slit loss. The effect of the non-uniform response of the NB816 filter on SuprimeCam is negligible for MSDM 80+3, because our measured wavelength is near the central wavelength of the NB816 transmission. Furthermore, lines at wavelengths away from the center of the NB816 bandpass would have decreased the observed Ly_{α} flux relative to our spectroscopic measurement—the opposite of what we observe. Generally, sources found through blind spectroscopy do not fall at the center of the slit; for larger samples the impact of slit losses on the LF is modeled statistically.

3.2. Properties

Equivalent widths, UV luminosities, and UV-continuum-derived SFRs are given in Table 1. We assume a flat UV spectrum (f_{UV} \propto \lambda^{-2}), consistent with observations of LAEs with Ly_{α} luminosities and redshifts similar to those of our objects (Pirzkal et al. 2007) and with z ~ 6 LBGs in the NICMOS UDF (Stanway et al. 2005; Bouwens et al. 2009). Therefore, although the center of the J_{110} filter corresponds to ~1700 Å in the rest frame, our best estimate is that k-corrections are negligible. We note that M_{UV} = −20.2 at z ~ 6 (Bouwens et al. 2007), so the UV luminosities that we measure are consistent with typical sources observed at this redshift—within a factor of 2 of L^{*} for the two J_{110}-detected sources.

SFRs are derived using the 1500 Å conversion from Madau et al. (1998). UV-continuum-based estimates of SFRs are thought to be more reliable than those from Ly_{α}; nevertheless, these continuum-based estimates come with several caveats. First, the conversion is valid only when the characteristic stellar age is older than the main-sequence lifetime of O- and B-stars. At young ages (<20 Myr), the true SFR may be a few times larger. Second, we have not corrected the UV luminosities for dust extinction, so again the SFRs given in Table 1 may be underestimated. However, in general, z ~ 6 galaxies are not thought to be very dusty (Bouwens et al. 2009), so dust corrections to our SFRs need not be very large. Third, uncertainties in the initial mass function (IMF) slope and mass cutoffs may be just as important, as they can change the SFR by a factor of a few (Henry et al. 2009). On the other hand, the two-photon nebular continuum is not expected to make a significant contribution to the UV luminosity, since it is generally dwarfed by the stellar contribution. While some sources are purported to have spectra dominated by the two-photon continuum, such objects appear to be rare (Fosbury et al. 2003; Raiter et al. 2010) and are predicted to have rest-frame Ly_{α} equivalent widths >1000 Å (Schaerer 2002, with coefficients from Aller 1984).

The equivalent widths that we measure are consistent with those of LAEs at high redshift, as shown in Figure 3. We do not make any correction for IGM absorption on the Ly_{α} emission, as has been done for some objects at z ~ 6 (e.g., Shimasaku et al. 2006). While it is possible that the Ly_{α} emission emergent from the galaxy is larger than observed, the amount of attenuation is uncertain because the resonant scattering of Ly_{α} photons shifts the emission toward redder wavelengths (Verhamme et al. 2008). It is not surprising that we do not observe any sources that are both UV luminous and have high-equivalent widths. As Nilsson et al. (2009) point out, this may be a consequence of both classes of objects being rare rather than a correlation of equivalent width with UV luminosity as has been suggested by Ando et al. (2006).

The three LAEs that we present are consistent with the range of equivalent widths that are easily explained by “normal” stellar populations, with ages older than 10 Myr and a Salpeter IMF. However, deeper continuum observations of MSDM 80+3 could prove that its equivalent width is much larger. There are several different models that can explain very large equivalent widths. First, extremely young ages and/or top-heavy IMFs can result in W_{0} > 240 Å (e.g., Malhotra & Rhoads 2004). Second, a
multi-phase interstellar medium has sometimes been invoked to preferentially absorb UV-continuum photons (Neufeld 1991; Hansen & Oh 2006; Scarlata et al. 2009; Finkelstein et al. 2009). Third, gravitational cooling radiation in the absence of star formation is predicted to result in $W_0 > 1000$ Å (Dijkstra 2009). However, such high-equivalent width objects are probably rare, as only a few sources in Figure 3 lie at $W_0 > 240$ Å. It is important to note that the uncertainty on such high-equivalent width sources typically exceeds 100 Å because of weak continuum detections, so these measurements should be viewed with caution.

It is interesting to consider whether the LAEs in our survey would be selected as $i$-dropout LBGs at $z \sim 6$, because the connection between the two populations is currently unclear. While it is generally understood that LAEs can be missed by LBG searches when their continuum is too faint, the selection of brighter sources can also be influenced by strong line emission (e.g., Stanway et al. 2007, 2008). At $z \leq 5.7$, Ly$\alpha$ falls in the i band, and galaxies can sometimes be too blue in $i$-$z$ to be included in i-dropout samples, even when an identical galaxy without Ly$\alpha$ emission would be included in such a sample. (It is worth noting that such objects could be included in $z \sim 5$ R-dropout samples, provided that the $i$-$z$ color is not too red.) Strong Ly$\alpha$ emission may influence the color selection of all three galaxies presented here. Assuming a flat UV slope ($f_\lambda \propto \lambda^{-2}$), we estimate $i$-$z = 1.2$ and $1.3$ for MSDM 29.5 and MSDM 71.5–5, near the $i$–$z = 1.3$ cut used by most LBG studies (e.g., Bouwens et al. 2007). The inclusion of sources such as these would depend on photometric scatter and the true value of the UV slope. On the other hand, MSDM 80+3, which is not detected in the $J_{110}$ images, would be unlikely to be included in i-dropout samples. The Ly$\alpha$ flux contributes substantially to the i band, so even in the absence of any continuum we would expect $i = 27.6$. Assuming $z_{580} > 26.9$—as inferred from our $J_{110}$ limit—implies that we would expect $i-z \lesssim 0.7$. Therefore, even if MSDM 80+3 could be detected in very deep imaging such as the UDF, it would be too much blue to be included in the i-dropout samples. This exercise emphasizes the importance of including Ly$\alpha$ emission in the modeling of LBG selection functions, as is done by Bouwens et al. (2007).

4. CONCLUSIONS

Spectroscopic searches for high-redshift emission-line galaxies have now been shown as a viable technique for improving sensitivity to faint emission-line galaxies (Santos et al. 2004; Sawicki et al. 2008; Lemaux et al. 2009). In particular, Martin et al. (2008) have successfully identified three $z = 5.7$ LAEs with multislit narrowband spectroscopy. We have presented NICMOS observations of these three LAEs, obtained with the high spatial resolution NIC2 camera. These images confirm the two sources which had only previously been seen in our IMACS spectroscopic observations. Furthermore, the $J_{110}$ data provide some constraints on the properties of these galaxies. We find that the UV luminosities, SFRs, equivalent widths, and sizes are all consistent with a redshift of $z = 5.7$. The two detected sources have $L_{UV}$ within a factor of 2 of $L_{UV}^\ast$ (as measured by Bouwens et al. 2007), and equivalent widths are well within the range of values seen at all redshifts. In addition, the non-detection of MSDM 80+3, in combination with a substantial slit loss of Ly$\alpha$ flux, suggests that the source may be somewhat extended.

These new observations further prove the success of multislit narrowband spectroscopy as a means to uncover faint, high-redshift emission-line galaxies. Further efforts for extending this technique to much fainter LAEs are already underway (A. Dressler et al. 2010, in preparation). Longer exposures with the recently upgraded IMACS detectors can reach Ly$\alpha$ luminosities at $z \sim 6$ that have previously only been realized in gravitational lensing surveys along the critical lines of galaxy clusters (e.g., Santos et al. 2004). At the limit of our new survey (at least $4 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$), rest-frame equivalent widths above 150 Å would imply a z-band magnitude fainter than 29—a regime that is currently only accessible from the small area covered by the UDF and UDF Parallels. These new blind spectroscopic observations will provide an ideal sample of low-luminosity $z = 5.7$ LAEs that will be detectable with NIRCAM, NIRSPEC, and the Tunable Filter Imager on the James Webb Space Telescope in modest exposure times ($\lesssim 10,000$ s). Such future observations will provide critical insight into the building blocks of galaxies by measuring their stellar and nebular (line-continuum) emission.

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