GEMINI H-BAND IMAGING OF THE FIELD OF A Z=10 CANDIDATE

M. N. BREMER
Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

JOSEPH B. JENSEN
Gemini Observatory, 950 N. Cherry Ave., Tucson, AZ 85719

M. D. LEHNERT, N. M. FÖRSTER SCHREIBER
Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, 85748 Garching bei München, Germany

AND

LAURA DOUGLAS
Department of Physics, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

accepted for publication in ApJ Letters

ABSTRACT

We present a deep H-band image of the field of a candidate z=10 galaxy magnified by the foreground (z=0.25) cluster Abell 1835. The image was obtained with NIRI on Gemini North to better constrain the photometry and investigate the morphology of the source. The image is approximately one magnitude deeper and has better spatial resolution (seeing was 0.4-0.5 arcsec) than the existing H-band image obtained with ISAAC on the VLT by Pelló et al. (2004). The object is not detected in our new data. Given the published photometry (H<sub>AB</sub>=25.0), we would have expected it to have been detected at more than ∼7σ in a 1.4 arcsec diameter aperture. We obtain a limit of H<sub>AB</sub>≥26.0 (3σ) for the object. A major part of the evidence that this object is at z=10 was the presence of a strong continuum break between the J and H band, attributed to absorption of all continuum shortward of 1216 Å in the rest-frame of the object. Our H-band non-detection substantially reduces the magnitude of any break and therefore weakens the case that this object is at z=10. Without a clear continuum break, the identification of an emission line at 1.33745 µm as Ly<sub>α</sub> at z ≥ 10 is less likely. We show that the width and flux of this line are consistent with an alternative emission line such as [OIII]λ5007 from an intermediate redshift HII/dwarf galaxy.

Subject headings: cosmology: observations - early universe - galaxies: distances and redshifts - galaxies: evolution - galaxies: formation

1. INTRODUCTION

Eight-meter class telescopes such as Gemini, VLT and Keck have opened up the Universe at z ≥ 5 for detailed study. The first z ≥ 5 galaxy was discovered in 1998 (Dev et al. 1998). In the past two years the number of confirmed and candidate z ≥ 5 galaxies has grown substantially, (see e.g., Lehner & Bremer 2003, Bremer et al. 2004, Stanway et al. 2004a,b, Bunker et al. 2003, Ajiki et al. 2003, Rhoads et al. 2003, Bouwens et al. 2004, Hu et al. 2004). These have been discovered using a variety of techniques including slitless spectroscopy, narrow-band imaging surveys for Lyα emitters, and broad-band photometry followed by spectroscopy to identify UV-bright Lyman dropouts.

Until recently, most searches for distant galaxies have concentrated on redshifts out to z ∼ 6.6. Beyond 7000 Å the sky emission is increasingly dominated by OH emission bands, making spectroscopic identification of Lyα emission more and more difficult, except in the gaps between the OH bands. As a consequence the redshift distribution of z > 5 galaxies with spectroscopic redshifts is non-uniform, mostly reflecting the wavelength distribution of these gaps. Nevertheless, with 8m telescopes it is entirely possible to unambiguously identify galaxies at z ∼ 5-6, (see e.g., the spectra in Lehner & Bremer 2003, Ando et al. 2004). Beyond 9000 Å the sky shows a higher density of bright telluric lines and a brighter continuum. As the typical z ∼ 5-6 galaxy has a continuum magnitude of AB ≥ 25 and a roughly flat intrinsic f<sub>L</sub> spectrum (zero color in AB), this makes identifying candidates at even higher redshifts increasingly difficult.

Nevertheless, surveys for even more distant galaxies are particularly important for our understanding of reionization. The likely presence of Gunn-Peterson troughs in the spectra of z > 6 SDSS quasars (Becker et al. 2001; Dijkstra et al. 2001; Fan et al. 2002) indicate that the reionization of hydrogen in the IGM ended at z ≥ 6. Reionization may have begun much earlier; analysis of Wilkinson Microwave Anisotropy Probe (WMAP) first-year temperature and polarization data indicates possible substantial reionization at z > 10 (Kogut et al. 2003). As the UV emission from early star-forming galaxies is thought to be a major (and possibly dominant) source of ionizing photons, the evolution in the number and luminosity of such galaxies is likely to be directly linked to the reionization history of the IGM. Based on work carried out thus far to z ∼ 6 it appears that the Universal UV luminosity and star formation density declines with increasing redshift beyond z ∼ 3 (e.g., Lehner & Bremer 2003, Bunker et al. 2004). If this trend continues beyond z = 6, it is difficult to envisage star formation in moderate mass galaxies being responsible for ionizing the Universe at z > 6 (see e.g., Ricotti et al. 2004).

One technique developed to overcome the difficulty of detecting even more distant galaxies is the use of gravitational lensing by an intervening galaxy cluster to boost their appa-
ent brightness. This boost can be as much as a factor of 10-100 if the galaxy happens to lie on a critical line. Santos et al. (2004) proved the utility of this technique out to $z = 5.6$ and Kneib et al. (2004) discovered a probable lensed $z \sim 7$ Lyman break galaxy behind Abell 2218.

Recently, Pelló et al. (2004) identified a highly magnified galaxy at $z=10$ lying on a critical line of the cluster Abell 1835. Using broad-band optical imaging from HST and CFHT along with near-IR imaging and spectroscopy from ISAAC/VLT, they presented evidence for a redshift of 10. The object was not detected in $V$, $R$, $I$ optical bands and was formally only detected at more than $4\sigma$ in $H$ ($H_{AB} = 25.00 \pm 0.25$) and about $3\sigma$ in $K$ ($K_{AB} = 25.51 \pm 0.36$). The $J$-band detection quoted by Pelló et al. was $J_{AB} = 26.8 \pm 1$. $J$-band spectroscopy covered the wavelength range 1.162 to 1.399 $\mu$m and showed an emission line at 1.33745 $\mu$m, detected in two separate central wavelength settings of the spectrograph, with a combined significance level of $4 - 5\sigma$.

This photometry and spectroscopy led Pelló et al. to argue that the emission line is most likely $\text{Ly}\alpha$ at $z=10.0175$. A key part of this case was the shape of the spectral energy distribution measured from the imaging data. The object was undetected in the optical, showed a large break between the $J$ and $H$ bands, and had a blue $H - K$ color ($H_{AB} - K_{AB} < 0$). This spectral energy distribution is consistent with a young stellar population observed at $z \sim 10$, with light shortward of 1216Å in the rest-frame heavily absorbed by intervening neutral hydrogen. This is consistent with the detected line being $\text{Ly}\alpha$ at $z=10.0175$.

However, given the low signal-to-noise detection, the extremely low flux of the emission line and the limited wavelength coverage by the spectroscopy, other emission line identifications are plausible (e.g., [OIII]5007, one component of the [OIII]3727 doublet, $\text{H}_\beta$). Although Pelló et al. claim the source is on a $z = 10$ critical line for Abell 1835, which could be used as a compelling evidence of its extreme redshift, there is no published detailed analysis of the accuracy of the mass model. The critical lines for other redshifts are close to those at $z = 10$, so uncertainty in the mass model can lead to the source falling on or near a critical line of a different redshift. This uncertainty is reflected in the range of magnifications given in Pelló et al. (2004). With all of the uncertainties in the other pieces of evidence that the source is at $z=10$, the strength of the $H$-band detection is key to this interpretation; without a strong break between $J$ and $H$, there is no other compelling evidence that the line should be identified as $\text{Ly}\alpha$.

Therefore, given the crucial role of the $H$-band imaging in assigning a redshift to this object, we here report on deep $H$-band images of the field of the $z=10$ candidate obtained with the Near-Infrared Imager (NIRI) on the Frederick C. Gillett Gemini Telescope (Gemini-North). These images were obtained both to better constrain the $H$-band photometry (the original detection was not highly significant) and to investigate the morphology of the source with images taken under the excellent seeing conditions that are often attainable at Gemini-North.

2. DATA AND ANALYSIS

2.1. Observations and Data Reduction

NIRI observations of Abell 1835 were carried out using Director’s Discretionary Time on the nights of 30 May and 6 Jun 2004 UT. NIRI is an infrared imager with 0.117 arcsec pixels and $2 \times 2$ arcm$^2$ field of view. We obtained a total of 22,635 s integration over 2 nights in the $H$ filter centered at 1.65 $\mu$m (1.49 to 1.78 $\mu$m). The weather was photometric and the seeing was good for both nights. On the first night, the image quality of the final image was 0.40 arcsec FWHM for 11,340 s of exposure. The second night was less good, and the overall image with 11,295 s of total exposure had 0.53 arcsec FWHM. The images were centered on the location of the $z=10$ candidate, rather than the center of the cluster (as was the Pelló et al. data), to allow better sky subtraction.

Individual 45 s exposures were reduced using the Gemini IRAF package. Each frame was sky-subtracted and flattened using flat field images produced by the Gemini calibration unit. A unique sky image was derived for each individual exposure by averaging the nearest 8 to 11 frames taken within 6 min, with stars and galaxies masked out. Since the $z=10$ candidate is located in a relatively low density region of the cluster, residual background variations due to incomplete masking of extended galaxies are not severe. Individual sky-subtracted and flat-fielded frames were then registered using integer shifts, averaged without any weighting, and cosmic rays were rejected. Data from the two nights were reduced separately, and later combined to produce the final image. The image quality in the combined image is 0.47 arcsec FWHM. Figure 1 shows the region around the candidate object.

Two UKIRT faint standard stars (Hawarden et al. 2001) were observed and reduced in the same way as the cluster data to determine the photometric calibration. The calibration determined for these two nights agreed to within 0.01 mag with the extinction-corrected zero point over the two month period prior to our observations. We obtained a zero point at $H$-band of 24.146 (compared to the NIRI mean of $H=24.14$ measured over many months). Our measured average sky brightnesses were $H=14.15$ and 14.27 mag per square arcsec for the two nights (typical for Mauna Kea). The sky variations throughout all nights were a smooth function of airmass, with the vast majority of data frames having values within 0.1 magnitudes of the above averages. In addition, NIRI uses Hall effect sensors to identify which filter is in the telescope beam. These identify in a unique and absolute way a given filter making it impossible to have an inappropriate filter in the beam. The zero points and sky brightnesses are in excellent agreement for NIRI in the $H$-band and are inconsistent with any filter other than $H$.

For comparison, we retrieved the raw ISAAC/VLT data used by Pelló et al. from the ESO data archive and re-reduced their $H$-band data. The resulting image is also shown in Figure 1 with the same display parameters as the NIRI/Gemini image. The final ISAAC $H$-band image was made from the same $H$-band data as presented in Pelló et al., as judged by comparing the total integration time listed in their paper with the total integration time of data we reduced (i.e., all the data from ESO programme ID 70.A-0355).

2.2. Photometry

To assess our ability to reliably detect objects with $H_{AB} = 25.0$ (the magnitude of the $z = 10$ candidate measured by Pelló et al., 2004), we added twenty-eight artificial stars with $H_{AB} = 25.0$ and 0.47 arcsec FWHM to the final Gemini image, three of which are shown in Figure 2. The mean recovered magnitude for these objects was $H_{AB} = 25.035$, with 1$\sigma$ uncertainties on each measurement typically 0.18 magnitudes. The aperture used for photometry was a circle of diameter 3 times the seeing disk (a diameter of 1.4 arcsec). The good
agreement between input and recovered magnitudes indicate that no aperture correction is necessary. The artificial sources are similar in brightness to the four faint objects marked in Figure 2 and suggest what the Pelló et al. object should look like if it were present in our image. All of the objects were easily detected in the NIRI image (see Figure 2).

Despite this, our Gemini H-band image shows no sign of an object at the location of the z=10 galaxy candidate. Given the measured sky noise and the results of our artificial star analysis, a point source with an AB magnitude of 25.0 would have been detected with a S/N ∼7–8 in a photometric aperture three times the seeing FWHM (1.4 arcseconds diameter). We randomly placed twenty-five 1.4 arcsec diameter apertures on sky regions within the target area shown in Figure 1 in order to determine detection limits for the candidate. The distribution of residual flux in these apertures gave a 3−σ limit of HAB > 26.30, a result which agrees with the measured uncertainties on the magnitudes of the artificial sources.

We also measured the distribution of the individual pixel counts about the mode of the sky value for the entire frame, after excising pixels containing flux from identified objects. This more conservative approach takes into account systematic variations in sky level due to subtracting the individual unique sky images, which are inevitably influenced by small amounts of flux from objects not fully masked out when creating the images. The resulting 3−σ limit of HAB > 26.03 differs from the aperture determination by 0.27 magnitudes, indicating that these systematic uncertainties are minor. Although, as noted above, these systematic uncertainties are likely to be less of an issue in the region of the candidate than for the frame as a whole, for the rest of this paper we use the more conservative limit of HAB > 26.0 for the flux at the position of the z=10 candidate.

Several objects detected in the region of our image shown in Figure 2 have magnitudes comparable to or somewhat fainter than the H-band magnitude for the candidate z=10 galaxy. Four of these objects lie within 15 arcsec of the z=10 candidate and provide a robust indication of the depth of the image. Object brightnesses were determined using the IRAF apphot photometry package. All four have measured S/N ≥5 within an aperture 1.4 arcsec in diameter. The positions of these four comparison objects are shown in Figure 2, and their brightnesses are listed in Table 1.

3. DISCUSSION

The lack of an H-band detection in our Gemini North NIRI data at a level significantly fainter than the detection by Pelló et al. (2004) is puzzling. Our observations are deeper (by about one magnitude), and have better spatial resolution and sampling. It is possible that the object is time-variable or transient, in which case non-concurrent multi-band photometry does not constrain the redshift, or has a large proper motion (i.e., is a solar system object: the ecliptic latitude of the source is about 14 degrees) given the range of dates over which the ESO data were obtained and the time elapsed between the Gemini and VLT observations.

In any event, our non-detection in H greatly weakens the argument based on the large break between the optical, J, and H bands which supported the claim that the line detected in the spectroscopy is most likely Lyα at z = 10.0. Given the photometry in J reported by Pelló et al., there is no formal continuum detection in the optical or J. The photometry by Pelló et al. indicates the object is only marginally detected in H (∼4σ; HAB = 25.00 ± 0.25) and K (3σ; Ks,AB = 25.51 ± 0.36). With our new H-band data (HAB > 26.0), the broad-band photometry can no longer be said to constrain the redshift of this object at all.

This leaves the ~4σ detection of the emission line from the spectroscopy. Recently Weatherley et al. (2004) have thrown doubt on the reality of this line. Taken together with our work, the reality of any source at this position has to be strongly questioned. However, whereas our work is based on an independent data set, Pelló et al. (2004) reanalyse the Pelló et al. data. It is possible that small differences in reduction may lead to contentious results, especially given the faintness and low signal-to-noise of the detection claimed by Pelló et al. (2004). Consequently, the following discussion assumes that the line is real. But even if it is not, the discussion is directly relevant to all searches for high redshift line emitters.

It is still possible that this line is Lyα at z=10, but with only this level of detection and no corroborate from photometry, the case is weakened considerably and perhaps this is not the most likely interpretation. Other lines such as [OII], [OIII], Hα at redshifts between 0.77 < z < 2.75 were detectable given the wavelength range used in the spectroscopy. The H − K_s color can no longer be used as evidence for an intrinsically blue and hence extremely young high redshift galaxy, given our sensitive upper limit.

Luminosity distributions for high redshift objects in Steidel et al. (1999) indicate that there should be several tens of low continuum luminosity galaxies per square arcminute between 0.77 < z < 2.7 with continuum fluxes below the optical flux limits quoted in Pelló et al. (2004). Indeed, Richard et al. (2003) discovered a faint z = 1.7 galaxy using the same imaging and spectroscopic data as used by Pelló et al. This object was identified in continuum longward of the I band from imaging and in three emission lines from spectroscopy. A comparable galaxy several times fainter in both continuum and lines would have been undetected in the photometry and would have only been detected in a single narrow line. Thus it remains possible that the Pelló et al. object is a galaxy of this type, almost regardless of which of the above emission lines is the true identification.

HII dwarf galaxies in the local universe and at moderate redshifts show a correlation between Hβ luminosity and emission line widths (Melnick, Terlevich, & Terlevich 2000). Pelló et al. measure a line flux of ~4×10^{-18} ergs cm^{-2} s^{-1} and an upper limit to the line width of about 60 km s^{-1}. If we assume the galaxy to be at redshift appropriate for the most likely alternative line identifications such as [OII]λ3726, [OIII]λ3792, [OIII]λ5007 or Hα, a reasonable range of ratio of Hβ to these other lines for dwarf galaxies, and a small amount of magnification due to the intervening cluster, we find that the emission line plausibly lies along the correlation of Melnick, Terlevich, & Terlevich (2000) for line width versus Hβ line luminosity. As an example, suppose that the actual line identification is [OIII]λ5007 at a redshift of 1.67, leading to a luminosity of 40.9 ergs s^{-1} in the log assuming reasonable cosmological parameters (H_0=70 km s^{-1} Mpc^{-1}, Ω_matter=0.3 and Ω_Λ=0.7). For HII/dwarf galaxies, the ratio of [OIII]λ5007 to Hβ ranges from about 2 to up to 10, consequently the Hβ luminosity would be between 39.9 to 40.6 ergs s^{-1} in the log. For the published line width, this range in luminosity falls on the correlation between line luminosity and width given by Melnick, Terlevich, & Terlevich for HII/dwarf emission line galaxies, showing that identifying this line as an optical emission line from a moderate redshift
HII/dwarf galaxy is plausible.

We wish to thank the pair of anonymous referees for their insightful and encouraging comments, and Roser Pelló, Daniel Schaerer, and Dan Stern for their helpful comments. These results are based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina). These Gemini observations were supported by Director’s Discretionary Time. The data retrieved from the ESO data archive were from observations made with the Paranal Observatory under programme ID 70.A-0355(C). LD acknowledges receipt of a PPARC studentship.

REFERENCES

Pelló, R., Haehnelt, M. G., Pettini, M., & Rees, M. J.
Ricotti, M., Haehnelt, M. G., Pettini, M., & Rees, M. J.
Rhoads, J. E. et al. 2003, AJ, 125, 1006
Gemini imaging of a z=10 candidate

Fig. 1.— Deep H-band NIRI image of the region around the z=10 candidate object (left) and our reconstruction of the ISAAC/VLT H-band image (right). Both images are 18 by 22 arcsec, the NIRI image has 0.47 arcsec FWHM image quality, and both images are displayed with the same linear range and stretch with respect to their noise levels. The circles indicate the location of the candidate object, and are 1.4 arcsec in diameter. A comparison of the aperture (1.4 and 3.0 arcsec in diameter) magnitudes of 15 relatively bright ($H_{AB} \approx 19-23$) objects near the position of the candidate object (estimated using the average zero-point from the ESO web pages for ISAAC for the month around the time of the observations) suggests that the photometry between the ISAAC and NIRI images are consistent with an average difference of $<H_{AB, ISAAC} - H_{AB, NIRI}> = -0.09 \pm 0.10$ magnitudes, with no dependence on the $J-H$ color of an object.

Fig. 2.— The same Gemini data as in Figure 1, this time with positions of four other sources near the candidate object with $H_{AB} \geq 25$. These are barely visible in the VLT data shown in Figure 1. In addition, the objects labelled “Art” are artificial sources with $H_{AB} = 25.0$. The three artificial sources are an illustrative subset of 28 artificial point sources used to assess the detectability of objects with this brightness in our image. The photometry for sources 1-4, and these three artificial sources is given in Table 1.