A REDSHIFT z = 6.56 GALAXY BEHIND THE CLUSTER ABELL 370

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ABSTRACT

We report the discovery of a redshift z = 6.56 galaxy lying behind the cluster Abell 370. The object HCM 6A was found in a narrowband imaging survey using a 118 Å bandpass filter centered at 9152 Å in the Low-Resolution Imaging Spectrograph (LRIS) camera on the 10 m Keck II telescope. Candidate Lyα emitters were identified by the equivalent width of the emission and the absence of lower wavelength flux. HCM 6A is the first galaxy to be confirmed at redshift z > 6 and has W_Lyα(observed) = 190 Å, flux = 2.7 × 10^{-17} ergs cm^{-2} s^{-1}. Spectra obtained with LRIS confirm the emission line and the continuum break across the line and show an asymmetric line profile with steep falloff on the blue side. Deep Subaru near-infrared Cooled Infrared Spectrograph and Camera for OHS images in J, H, and K' that extend the sampled continuum to longer wavelengths give a consistent estimate of the continuum flux density in these line-free regions of (2.6 ± 0.7) × 10^{-20} ergs cm^{-2} s^{-1} Hz^{-1}. The line width and strength, asymmetric profile, and very deep spectral break are only consistent with the interpretation of the line as a redshifted Lyα feature. From the detailed lensing model of this cluster, we estimate a lensing amplification of 4.5 for this galaxy, which is located slightly over an arcminute from the center of the cluster, for an unlensed flux of 6.5 × 10^{-18} ergs cm^{-2} s^{-1}. The presence of such a galaxy suggests that the reionizing epoch is beyond z = 6.6.

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

1. INTRODUCTION

The study of the early universe through high-redshift galaxies has seen substantial progress in recent times, with a number of galaxies discovered at redshifts z > 5 (Dey et al. 1998; Hu, Cowie, & McMahon 1998; Weymann et al. 1998; Hu, McMahon, & Cowie 1999; Stern & Spinrad 1999; Ellis et al. 2001). Active galaxies associated with radio galaxies (van Breugel et al. 1999) have been seen to similar redshifts, and quasars have now been detected out to z = 6.28 from the Sloan survey (Fan et al. 2000, 2001; Anderson et al. 2001).

The present Letter describes a continuation of our narrowband filter survey (Cowie & Hu 1998; Hu et al. 1998, 1999), which probes Lyα emission from z = 3.4 → 5.7 to a redshift z ~ 6.5. At z = 3, the brightest Lyα emitters have line fluxes near 10^{-16} ergs cm^{-2} s^{-1} and a single, roughly 30 arcmin^2 field of the Low-Resolution Imaging Spectrograph (LRIS) camera on the Keck 10 m telescope yields a handful of objects to a flux limit of 10^{-17} ergs cm^{-2} s^{-1}. At z ~ 6.5, the fluxes drop near the sensitivity limit, and only occasional objects are expected to be found (e.g., Thommes 1999). Therefore, to improve our sensitivity limits we have targeted foreground massive lensing clusters, which can provide substantial amplification over a fraction of the LRIS field. We have also observed the well-studied blank fields used in the shorter wavelength narrowband searches. Even with the increased sensitivity provided by the lensing, detections are extremely rare and our observations have so far yielded only one compelling detection lying behind the cluster A370. We describe this object in the present Letter.

Discriminating Lyα emitters from lower z emission-line objects can be difficult at lower redshifts (Stern & Spinrad 1999), but as we move to higher redshifts the continuum break signature becomes so extreme that there is little likelihood of a misidentification provided we have sufficiently deep continuum images. Songaila & Cowie (2002) have used spectra of the Sloan quasars to measure the average transmission of the Lyα forest region as a function of redshift over the z = 4 → 6 range. Their results translate to a magnitude break across the Lyα emission line of

\[ \Delta m = 3.8 + 20.3 \log \left( \frac{1 + z}{7} \right) \].

Extrapolated to z = 6.5, this corresponds to a 4.5 mag break. If the epoch of reionization is at z ~ 6.1 as suggested by Becker et al. (2001), the continuum blueward of Lyα would be essentially black. However, as we shall consider further in § 3, in this case the radiation damping wings of the foreground neutral hydrogen extend through the Lyα emission and make it unlikely we would see Lyα emitters at all, so the presence of the A370 emitter argues for a higher reionization redshift.

In § 2, we summarize the narrowband observations and the continuum observations at longer and shorter wavelengths together with the spectroscopic followup. The properties of HCM 6A leave little doubt about its identification as a high-z Lyα emitter. Finally, in the discussion, we consider the implications
TABLE 1

| Field | R.A. (J2000.0) | Decl. (J2000.0) | Exposures | $t_{exp}$ (s) |
|-------|---------------|----------------|------------|---------------|
| A370ʻ   | 02 39 53.1    | −01 34 35     | 14 × 1500 s | 21000         |
| A851ʻ   | 09 43 02.6    | +46 58 58     | 19 × 900 s + 7 × 650 s | 21650         |
| HDF     | 12 36 52.0    | +62 12 30     | 12 × 1800 s | 21600         |
| SSA 17  | 17 05 00.0    | +43 59 35     | 6 × 1200 s | 7200          |
| A2390ʻ  | 21 53 34.6    | +17 40 10     | 11 × 1500 s | 16500         |
| SSA 22  | 22 14 58.2    | +00 00 00     | 9 × 1500 s | 13500         |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

*a* Cluster redshifts are $z = 0.37$ for A370, $z = 0.41$ for A851, and $z = 0.231$ for A2390. for early star formation and for the evolution of the intergalactic gas.

2. OBSERVATIONS

2.1. Narrowband Survey

The present images were obtained using a 118 Å filter centered on 9152 Å in the LRIS camera (Oke et al. 1995) on the Keck 10 m telescopes. This wavelength lies in a very dark region of the wavelength range of the OH (8–4) and OH (7–3) bands and corresponds to Lyα at a redshift of ~6.5. In total, six fields have been imaged with this filter and are summarized in Table 1. In each case, the exposures were made as a sequence of spatially dithered background-limited exposures, and median sky flats were used to flat-field the images. The images were calibrated with spectrophotometric standards. The deepest exposures, totaling about 6 hr per field, were taken on the Hubble Deep Field (HDF) and on fields centered on the clusters A370 and A851. Over most of the area in these fields, the $5\sigma$ limiting flux sensitivity is approximately $1.6 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$, but, for the massive clusters, there is a small area in the central regions where the lensing amplification provides a significant gain in sensitivity.

For each field, a very deep Z band ($\lambda_{eff} \sim 9170$ Å; Hu et al. 1999) was used to measure the continuum, and an extremely deep R-band image was used as a shorter wavelength reference to measure the continuum break. We searched each field for objects with observed equivalent widths in excess of 100 Å that were not visible in the $R$ image. Only one such object has been found in the six fields. Finding images for HCM 6A, which lies behind the massive lensing cluster A370 in a region of significant amplification, are shown in Figure 1, which compares narrowband and deep R-continuum images and gives coordinates. Insets show the continuum-subtracted image and the corresponding Wide Field Planetary Camera 2 (WFPC2) F675W image from the Hubble Space Telescope (HST). (See Bézecourt et al. 1999 for a description of the wider field of the HST image.)

The following subsections describe the observations made on this object to confirm that it is a high-redshift Lyα emitter rather than a lower redshift emission-line object.

2.2. Broadband Optical Imaging

Deep multicolor images of A370 were obtained using LRIS on the Keck 10 m telescopes on UT 1999 August 11, 1999 September 9–10, 2000 August 25, 2000 December 29, and 2002 January 11–12. The data were taken as a sequence of dithered exposures, with net integration times of 2400 s in V, 27,900 s in R, 4050 s in I, and 9820 s in Z. A deep B (3780 s) image was obtained with the Echellette Spectrograph and Imager on Keck II on UT 2000 September 29–30. The images were processed using median sky flats generated from the exposures. Conditions were photometric during these observations. The data were calibrated using the photometric and spectrophotometric standard, HZ 4 (Turnshek et al. 1990; Oke 1990), and faint Landolt standard stars in the SA 95-42 field (Landolt 1992).

2.3. Near-Infrared Imaging

We used the new Cooled Infrared Spectrograph and Camera for OHS (Motohara et al. 1998) on the Subaru 8.3 m telescope...
on UT 2000 June 18–19, July 15–16, September 10–12, and November 7 to obtain extremely deep \( J, H, \) and \( K' \) images of A370. The detector used was a 1024 \( \times \) 1024 HAWAII array. To minimize the image degradation, a number of subexposures were taken at each position in an eight-point pentagon pattern (5" step size). Weather conditions were photometric, and the seeing was typically 0\'3–0\'5 during the first three observing runs, which was also the resolution of nearly all the final reduced images. Conditions were clear, but with variable seeing during the November observing run, with characteristic image FWHM of \( \sim 0\'8 \) for the A370 \( H \) final image. The data were processed using median sky flats generated from the dithered images. The data were calibrated from observations of the UKIRT faint standards (Casali & Hawarden 1992) FS 27, FS 29, FS 6, and FS 10. The total exposure times were 13,280 s (\( J \)), 7680 s (\( H \)), and 15,360 s (\( K' \)).

2.4. Colors and Spectral Energy Distributions

HCM 6A is clearly detected at all wavelengths longer than the \( Z \) band, as is shown in Figure 2, where we present thumbnail images centered on the object, which is circled (left panels). However, it is not seen at any shorter wavelengths (right panels).

The spectral energy distribution of HCM 6A is shown in Figure 3, where the error bars are 1 \( \sigma \). At wavelengths above the \( Z \) band, the mean flux density averaged over the \( J, H, \) and \( K' \) bands is \( (2.6 \pm 0.7) \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \), while at shorter wavelengths averaged over the \( V \) and \( R \) bands the flux density is \( (0.1 \pm 2.9) \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \). At the 2 \( \sigma \) level, the continuum break exceeds 1.7 mag.

2.5. LRIS Spectroscopy

Spectra of the object were obtained with the LRIS during runs in UT 1999 September 16–18, 2001 January 23–24, and 2001 October 21. The observations were made in multislit mode using 1\h" wide slits with a variety of gratings. The emission line is clearly seen in all the spectra, and the stacked spectra show the line profile to be asymmetric, with steeper blue falloff as would be expected from the effects of the forest absorption. The redward continuum is most clearly seen in the spectra obtained with the 400 line mm\(^{-1} \) grating, which in combination with the slit width gives a resolution of roughly 11.8 A, and we show the combined spectra obtained in this mode in Figure 4. The strong emission line is at a wavelength of 9187 A, which corresponds to a redshift of \( z = 6.56 \) for Ly\( \alpha \). The continuum break is consistent with that obtained from the imaging data but is more poorly determined because of the uncertainties in the sky subtraction in the spectra.

3. RESULTS AND DISCUSSION

The absence of detections outside the cluster lensing regions places a 1 \( \sigma \) upper limit of 27 deg\(^{-2} \) for the number of sources in the filter bandpass (\( \Delta z = 0.1 \)) at the 5 \( \sigma \) flux limit of \( 1.6 \times 10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \) (the HDF limit) and 13 deg\(^{-2} \) at 2.7 \( \times \) 10\(^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \) (the worst limit in the six fields), which is broadly consistent with that expected from models (e.g., Thommes 1999) or extrapolation from lower redshifts.

We have used the Lenstool model of A370 described in Kneib et al. (1993) to measure an amplification of 4.5 at the position of HCM 6A, giving a demagnified flux of \( 6 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \). Lenstool also allows us to measure the corresponding source plane areas that would give such amplifications. For the combined A370, A851, and A2390 areas, the observed source plane area is 0.46 arcmin\(^2 \), with most of this area lying behind the most massive (A370) cluster. The surface density of objects above a flux limit of \( 4 \times 10^{-18} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \) is then between 1300 and 26,000 deg\(^{-2} \), where the range is \( \pm 1 \sigma \), which is also broadly consistent with the model expectations.

Equivalent width determination for very high \( z \) objects is complicated by the strong forest absorption on the blue side of the emission feature and across the \( Z \) band. For the 1\h" diameter aperture measurements shown in Figure 3, the equivalent width determined from the line flux and the average long-wavelength continuum flux above the emission feature is 190 A. If instead the average \( Z \)-band continuum is used as the reference value, the computed equivalent width increases to 325 A.

The brighter region of the object is clearly extended along an axis of about 110\h" in position angle with a maximum length of around 4\h". The elongation is consistent with the substantial distortion expected at this position if the galaxy lies at very high redshift, providing an additional weak confirmation of the redshift identification. The intrinsic size of the main region at the source plane is then around 1\h". The second fragment lies...
around 1" away from the brighter portion. At $z = 6.56$, with the currently favored Lambda cosmology ($\Lambda = 0.66$ and $\Omega = 0.33$) and $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, these angular sizes correspond to physical sizes of approximately 40 kpc.

After removing the lensing amplification, the continuum flux corresponds to a rest-frame ultraviolet luminosity of $2 \times 10^{39}$ ergs s$^{-1}$ Hz$^{-1}$, which may be used to estimate the star formation rate. For a Salpeter initial mass function extending to 0.1, this is about $40 M_\odot$ yr$^{-1}$. The rest-frame demagnified Ly$\alpha$ luminosity is $2 \times 10^{41}$ ergs s$^{-1}$, which, assuming case B recombination and using the Kennicutt (1983) translation of H$\alpha$ luminosity to star formation rate, would correspond to a rate of $2 M_\odot$ yr$^{-1}$. The lower value obtained from the Ly$\alpha$ luminosity presumably reflects the combined effects of dust extinction in the galaxy and destruction of the blue side of the emission line by scattering in the intergalactic medium.

Using the more robust UV continuum estimate, we find that the universal star formation rate at this redshift from this class of object lies in the range $0.13 \rightarrow 2.7 M_\odot$ Mpc$^{-3}$ yr$^{-1}$ ($\pm 1 \sigma$). This is quite similar to rates estimated at lower redshifts within the very large uncertainty (e.g., Barger, Cowie, & Richards 2000 and references therein).

Perhaps of most interest, given this is a single object and statistical inferences are therefore difficult, is that the presence of even a single object at this redshift may suggest we have not yet reached the redshift of reionization. In a pre-reionization epoch, the radiation damping wings from the neutral gas will black out regions extending about 20 Å to the redward of the Ly$\alpha$ wavelength in the observed frame of the object (Miralda-Escudé 1998; Miralda-Escudé & Rees 1998). While ultraluminous quasars can ionize their surroundings and prevent this effect, it is unlikely that a small Ly$\alpha$ emitting galaxy of the present type could do this, although it could lie in a large ionized region produced by some other source of ionizing photons.

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Fig. 4.—Spectrum of HCM 6A from a 4 hr exposure made with the LRIS using the 400 line mm$^{-1}$/H110021 grating. The emission line is at 9187 Å. The solid line near the axis shows the median continuum flux above the line and gives a break strength consistent with the broadband measurements. The solid line above the emission shows the 50% width of the narrowband filter, whose profile is shown overlaid on the fluxed night-sky spectrum, plotted at 1% strength above the object spectrum. Enlarged plots of the object’s emission feature and 1% of the night-sky background spectra taken with the 400 line mm$^{-1}$/H110021 grating are shown in the inset, where the asymmetry of the line profile can be clearly seen.
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ERRATUM: “A REDSHIFT $z = 6.56$ GALAXY BEHIND THE CLUSTER ABELL 370” (ApJ, 568, L75 [2002])

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In computing the continuum luminosity on page L78 of the above Letter, the lensing correction factor of 4.5 was omitted. The correct luminosity is $4 \times 10^{28}$ ergs s$^{-1}$ Hz$^{-1}$, and the star formation rate based on the red continuum light should read $9 M_{\odot}$ yr$^{-1}$. The universal star formation rate should read $0.013 \rightarrow 0.26 M_{\odot}$ Mpc$^{-3}$ yr$^{-1}$. 