

## A PROBABLE $z \sim 7$ GALAXY STRONGLY LENSED BY THE RICH CLUSTER A2218: EXPLORING THE DARK AGES<sup>1</sup>

JEAN-PAUL KNEIB,<sup>2,3</sup> RICHARD S. ELLIS,<sup>3</sup> MICHAEL R. SANTOS,<sup>3,4</sup> AND JOHAN RICHARD<sup>2,3</sup>

Received 2004 January 7; accepted 2004 February 17

### ABSTRACT

We discuss the observational properties of a remarkably faint triply imaged galaxy revealed in a deep  $z'$ -band Advanced Camera for Surveys observation of the lensing cluster A2218 ( $z = 0.175$ ). A well-constrained mass model for the cluster, which incorporates the outcome of recent Keck spectroscopic campaigns, suggests that the triple system arises via a high-redshift ( $z > 6$ ) source viewed at high magnification ( $\simeq 25$  times). Optical and infrared photometry from *Hubble Space Telescope* and the Keck Observatory confirms the lensing hypothesis and suggests that a significant discontinuity occurs in the spectral energy distribution within the wavelength interval 9250–9850 Å. If this break is associated with Gunn-Peterson absorption from neutral hydrogen, a redshift of  $6.6 < z < 7.1$  is inferred. Deep Keck spectroscopy conducted using both optical and infrared spectrographs fails to reveal any prominent emission lines in this region. However, an infrared stellar continuum is detected whose decline below 9800 Å suggests a spectroscopic redshift toward the upper end of the range constrained photometrically, i.e.,  $z \simeq 7$ . Regardless of the precise redshift, the source is remarkably compact ( $\lesssim 1 h_{70}^{-1}$  kpc) and faint ( $z_{F850LP} = 28.0$ ) yet is undergoing vigorous star formation at a rate  $\simeq 2.6 M_{\odot} \text{ yr}^{-1}$ . An intriguing property is the steep slope of the ultraviolet continuum implied by the photometry, which may suggest that the source is representative of an early population of galaxies responsible for cosmic reionization. Independent verification of these results is highly desirable, but our attempts highlight the difficulty of studying such sources with present facilities and the challenges faced in pushing back the frontiers of the observable universe beyond  $z \sim 6.5$ .

*Subject headings:* cosmology: observations — galaxies: evolution — galaxies: formation —  
galaxies: high-redshift — gravitational lensing

*On-line material:* color figures

### 1. INTRODUCTION

Reionization was a landmark event that imprinted a signature over the scale of the entire universe. After decades of lower limits on the redshift at which it occurred, recent observations of QSOs discovered by the Sloan Digital Sky Survey (Becker et al. 2001; Djorgovski et al. 2001; Fan et al. 2002) suggest that reionization was just finishing at  $z \sim 6$ –6.5. The discovery of  $z \simeq 6.5$  galaxies with strong Ly $\alpha$  emission (Hu et al. 2002; Kodaira et al. 2003) is illustrative of possible sources which may be responsible. Analysis of recent temperature and polarization fluctuation data from the *Wilkinson Microwave Anisotropy Probe (WMAP)* satellite suggests an optical depth for Thompson scattering of  $\tau = 0.17 \pm 0.04$ , implying that reionization began at higher redshift, perhaps as early as  $z \sim 15$ –20 (Kogut et al. 2003; Spergel et al. 2003).

The discovery of star-forming galaxies at  $z \simeq 6.5$  is an important step toward understanding the nature of the sources responsible for the end of cosmic reionization. However, to explore the earlier stages implied by the *WMAP* results, it is necessary to push the search for star-forming systems to higher redshifts. With current facilities, this is technically very

challenging. It is perhaps salutary to note that the current redshift frontier ( $z = 6.5$ , corresponding to an observed Ly $\alpha$  wavelength of 9200 Å) is coincident with the wavelength at which optical CCD detectors fall significantly in their quantum efficiency. Ground-based infrared spectroscopy, necessary for exploring sources at higher redshift, is especially difficult at faint limits.

Color-based searches for  $z > 6$  sources with the Advanced Camera for Surveys (ACS) on board the *Hubble Space Telescope (HST)* is now recognized as a valuable way of locating  $z > 6$  sources. Promising results have been obtained by utilizing the long wavelength F850LP ( $z'$ -band) filter in conjunction with deep infrared imaging on *HST* or with large ground-based telescopes (Bouwens et al. 2003; Yan et al. 2003; Stanway et al. 2004; Dickinson et al. 2004). In view of significant contamination of red “drop-out” samples by cool stars (e.g., Stanway et al. 2004), the primary challenge lies in spectroscopically verifying faint candidates (e.g., Dickinson et al. 2004). Neither optical nor infrared spectrographs on the current generation of ground-based telescopes may have the sensitivity to give convincing results unless strong emission lines are present. Although most of the distant sources found beyond  $z \simeq 5$  have been identified via strong Ly $\alpha$  emission (Stern & Spinrad 1999; Spinrad 2003), some sources should have weak or no Ly $\alpha$  emission (e.g., Spinrad et al. 1998). Indeed, a significant fraction ( $\sim 75\%$ ) of the most intensely star-forming galaxies located by color selection techniques at  $z \simeq 3$ , reveal Ly $\alpha$  only in absorption (Shapley et al. 2003).

Gravitational magnification by foreground clusters of galaxies, whose mass distributions are tightly constrained by arcs and multiple images of known redshift, has already provided

<sup>1</sup> Using data obtained with the *Hubble Space Telescope*, operated by AURA, Inc., for NASA and the W. M. Keck Observatory on Mauna Kea, Hawaii. The W.M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and NASA, and was made possible by the generous financial support of the W.M. Keck Foundation.

<sup>2</sup> Observatoire Midi-Pyrénées, UMR5572, 14 Avenue Edouard Belin, 31000 Toulouse, France.

<sup>3</sup> Caltech, Astronomy, 105-24, Pasadena, CA 91125.

<sup>4</sup> Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK.

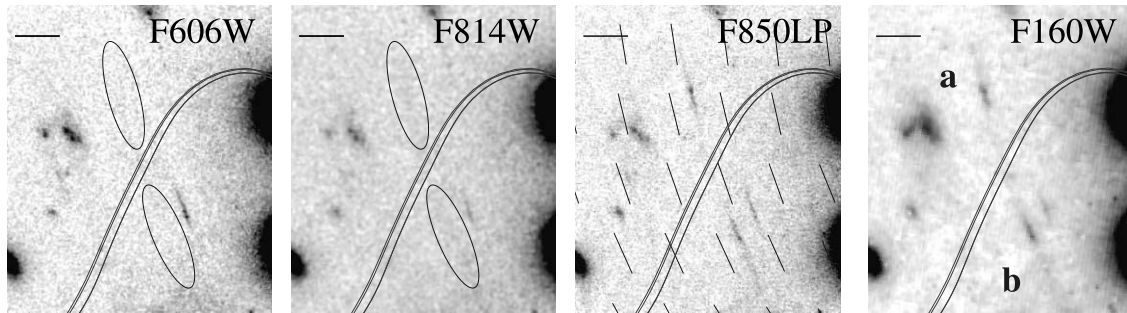


FIG. 1.—WFPC2-F606W, WFPC2-F814W, ACS-F850LP, and NICMOS-F160W images of A2218 of the new faint pair in the lensing cluster A2218 ( $z = 0.175$ ). The signals redward of the WFPC2-F814W observation suggest a marked break occurs in the continuum signal at around 9600 Å. curves correspond to the predicted location of the critical lines at  $z_s = 5, 6.5,$  and  $7$  (from bottom to top, the latter two being almost coincident). The scale bar at the top left of each image represents  $2''$ . The predicted shear direction (*thin segments*) closely matches the orientation of the lensed images. [See the electronic edition of the Journal for a color version of this figure.]

new information on the abundance of high-redshift objects (Kneib et al 1996; Santos et al. 2004). Particularly high magnifications ( $\simeq 10$ – $50$  times) are expected in the “critical regions,” which can be located precisely in well-understood clusters for sources occupying specific redshift ranges (Ellis et al. 2001). Although the volumes probed in this way are far smaller than those addressed in panoramic narrowband surveys (Hu et al. 1998, 2004; Malhotra et al. 2001) or the color-based surveys cited earlier, if the surface density of background sources is sufficient, lensing may provide the necessary boost for securing the first glimpse of young cosmic sources beyond  $z \simeq 6.5$  (Santos et al. 2004).

In the course of studying the detailed rest-frame properties of the image pair of a lensed  $z = 5.576$  galaxy in the cluster A2218 (Ellis et al. 2001), we have discovered a new faint pair of images in a deep  $z'$ -band ACS observation of this cluster. On the basis of the geometrical configuration of this pair and its photometric properties, we concluded that the images most likely arise via strong magnification of a distant  $z > 6$  source. The implied high redshift of this source led us to explore its properties in more detail.

The plan of the paper is as follows. We present the photometric observations in § 2. Section 3 discusses redshift constraints determined independently from the lensing model of A2218 and the spectral energy distribution (SED) based on broadband photometry. Section 4 summarizes our attempts to detect Ly $\alpha$  emission spectroscopically and discusses the implications of a continuum discontinuity seen in the infrared spectrum. We discuss the source properties and implications further in § 5. Throughout we assume a cosmological model with  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 2. PHOTOMETRIC OBSERVATIONS

The source in question was originally discovered as a pair of images (Fig. 1, *a* and *b*) with reflection symmetry and a separation of  $7''$  in a deep (five-orbit, 11.31 ks) *HST* ACS-F850LP ( $z'$ -band) observation of the A2218 cluster of galaxies. The observation was conducted as part of GO program 9452 (PI: Ellis) to characterize the stellar continuum in the lensed pair at  $z = 5.576$  discussed earlier by Ellis et al. (2001).

The new ACS images were reduced using standard IRAF<sup>5</sup> and STSDAS routines. The source was found by blinking

the reduced F850LP image with two archival images taken at shorter wavelength with the F814W and F606W filters of the Wide Field Planetary Camera 2 (WFPC2) (SM-3a ERO program 8500, PI: Fruchter; exposure time F606W: 10 ks, F814W: 12 ks). A prominent discontinuity in the brightness of the pair can be seen viewing, in sequence, the F850LP, F814W, and F606W frames (Fig. 1). Together with the geometrical arrangement and symmetry of the pair in the context of our mass model for A2218, this suggested the source is at high redshift and gravitationally magnified by the cluster (see § 3).

The two images have similar appearance in the *HST* NICMOS F160W image. These *H*-band data were also obtained under the GO program 9452 and were acquired in a four-orbit continuous viewing zone observation totaling 22.2 ksec of exposure time. Similarly, we also identified the lensed pair in a deep Keck NIRC *J*-band image (5.64 ks exposure) taken in  $0''.65$  seeing on 2002 July 22 and 23 (A. Blain & N. Reddy 2003, private communication).

A clear mirror symmetry is seen in the *HST* data; both images contain a bright core, a second fainter knot, and extended emission of lower surface brightness. The orientation of the pair also closely matches the predicted shear direction (Fig. 1). The lensing hypothesis is further verified by comparing the colors of the two images *a* and *b* using the available photometric data summarized in Table 1.<sup>6</sup> Colors were computed using a fixed elliptical aperture and are identical for both images within the uncertainties. (For the  $z_{850LP} - J$  color, the ACS  $z'$ -band image was convolved by a Gaussian to match the seeing of the Keck NIRC *J* image).

## 3. REDSHIFT CONSTRAINTS

### 3.1. Gravitational Lensing

In the context of the tightly constrained mass model of A2218 (Kneib et al. 1996), updated to include the properties of the  $z = 5.576$  pair identified by Ellis et al. (2001) and the more recent confirmation of a triply imaged submillimeter selected source at  $z = 2.515$  (Kneib et al. 2004a), the symmetry expected for a lensed pair around the critical line implies a source redshift  $z_s > 6$  (see curves in Fig. 1). The absolute location of the  $z = 6$  critical line is particularly well understood in this region from the measured symmetry of the adjacent  $z = 5.576$  pair around its critical line shown in Figure 2.

<sup>5</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

<sup>6</sup> All photometric quantities are based on the Vega system.

TABLE 1  
OBSERVED PHOTOMETRY FOR THE TRIPLE SYSTEM

FILTER	IMAGE		
	<i>a</i>	<i>b</i>	<i>c</i>
$\alpha_{J2000}$ .....	16 35 54.73	16 35 54.40	16 35 48.92
$\delta_{J2000}$ .....	66 12 39.00	66 12 32.80	66 12 02.45
$V_{606W}$ .....	not detected	not detected	not detected
$I_{814W}$ .....	$26.5 \pm 0.2$	$26.4 \pm 0.2$	not detected
$z_{850LP}$ .....	$24.38 \pm 0.05$	$24.54 \pm 0.05$	$25.9 \pm 0.1$
$J$ .....	$23.4 \pm 0.3$	$23.5 \pm 0.3$	...
$H_{160W}$ .....	$22.96 \pm 0.06$	$23.01 \pm 0.07$	...
$V_{606W}-z_{850LP}$ .....	$>3.6$	$>3.5$	$>2.1$
$I_{814W}-z_{850LP}$ .....	$2.1 \pm 0.2$	$1.9 \pm 0.2$	$>1.8$
$z_{850LP}-J$ .....	$1.0 \pm 0.3$	$1.0 \pm 0.4$	...
$z_{850LP}-H_{160W}$ .....	$1.42 \pm 0.1$	$1.53 \pm 0.1$	...
Magnification.....	$25 \pm 3$	$25 \pm 3$	$5.3 \pm 0.5$

NOTES.— $3\sigma$  detection limits for a point source:  $V_{606W} = 28.0$ ,  $I_{814W} = 27.2$ ,  $z_{850LP} = 26.7$ ,  $J = 24.4$ , and  $H_{160W} = 25.8$ . Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

However, the lensing configuration for the new source provides only a fairly weak constraint on the precise redshift beyond this lower limit since the location of the critical line does not change significantly beyond  $z \simeq 6$  (Fig. 1).

Our mass model for A2218 requires there to be a third image of the source, which we successfully located in the  $z'$ -band image at the expected position (Fig. 2c) and with the expected flux (Table 1). Although our photometric coverage of this third, fainter, image is not as complete as that for the primary pair (because of the smaller field of the infrared cameras used), importantly the *HST* photometry confirms the same discontinuity in flux seen between F850LP and F606W (Fig. 2; Table 1). The improved mass model suggests that all three images represent manifestations of a single source at  $z > 6$  magnified by a factor of  $\simeq 25$  (in the case of images *a* and *b*). The intrinsic (unlensed) source brightness is  $z_{850LP} = 28.0 \pm 0.1$ ,  $H_{160W} = 26.5 \pm 0.1$ .

### 3.2. Spectral Energy Distribution

Figure 3 summarizes the available broadband photometry for the brightest of the three images (Fig. 1a). We include, for completeness, the Keck NIRC  $J$  measurement, although, as a ground-based measurement, it is more adversely affected by crowding and background issues related to the adjacent luminous cluster members. Its low significance provides little more than evidence for a detection. Accordingly, we do not use the  $J$ -band data in any of the subsequent analysis.

A significant discontinuity in flux is apparent in the wavelength interval  $\lambda \lambda \sim 9200 \text{ \AA} - 1 \mu\text{m}$ . The overlap in sensitivity between the WFPC2 filter F814W and the ACS filter F850LP is of particular diagnostic use. If it is assumed the  $z > 6$  source has a UV continuum that rises to shorter wavelengths with a discontinuity produced by a Gunn-Peterson trough at around  $\lambda_{\text{rest}} = 1216 \text{ \AA}$ , the ratio of the F814W and F850LP fluxes can be used to estimate the redshift depending on the slope of the UV continuum.

Assuming the SED is given by a simple relation,  $f(\lambda) \propto \lambda^{-\alpha}$  for  $\lambda/(1+z) > 1216 \text{ \AA}$  and  $f(\lambda) = 0$  otherwise, the accurate *HST* photometry (F606W, F814W, F850LP, F160W) implies the discontinuity occurs in the wavelength interval 9250–

9850  $\text{\AA}$ , corresponding to  $6.6 < z < 7.1$  (Fig. 3, *dashed lines*).<sup>7</sup> The photometric redshift constraint is particularly firm at the lower end. Below  $z \simeq 6.6$  it is hard to justify the observed F814W and F850LP flux ratio regardless of the form of the SED. Therefore, in summary, the available *HST* photometry suggests the lensed source lies beyond  $z \simeq 6.6$ .

### 4. OPTICAL AND INFRARED SPECTROSCOPY

Given the possibility that the lensed source lies beyond a redshift  $z \simeq 6.6$  with a Gunn-Peterson discontinuity in the wavelength range 9250–9850  $\text{\AA}$ , we next tried to detect Ly $\alpha$  emission in this region using both NIRSPEC (McLean et al. 1998) on Keck II and the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) on Keck I. If around half of the flux in the F850LP band arises via a Ly $\alpha$  emission line, in a manner analogous to the  $z = 5.576$  source (Ellis et al. 2001), we consider that the LRIS campaign should be successful in securing the redshift, particularly since the lower part of the region to explore is, by good fortune, one of the “windows” of low OH sky emission used by narrowband imagers to locate Ly $\alpha$  emitters (e.g., Kodaira et al. 2003).

We used LRIS on two runs, 2003 May 31–June 1 and 2003 June 30–July 1 (see J.-P. Kneib et al. 2004, in preparation for a complete description of these data). During the first observing run, we observed the brighter pair of the triple system using the 600 line grating blazed at  $1 \mu\text{m}$  for a total of 13.8 ks. The first night offered relatively poor conditions (cirrus, high humidity), but 9.0 ks was secured on the second night in slightly better conditions. For these observations the wavelength coverage ranged from 6930 to 9500  $\text{\AA}$ . No signal was detected from either image.

During the second observing run, we used the same configuration and integrated for 9.2 ks in relatively good conditions with  $\sim 0''.8$  seeing. The wavelength coverage was extended slightly to the red to reach 9600  $\text{\AA}$ . In the following, only the second observing run will be utilized as the data quality is much better. Flux calibration was conducted using Feige 67, Feige 110, and Wolf 1346 spectrophotometric standards observed in twilight. The spectroscopic observations were reduced using IRAF. Despite the improved conditions, no continuum or emission lines were detected to 9600  $\text{\AA}$  from either image. The absence of any LRIS detection in the clean wavelength range 9000–9300  $\text{\AA}$  places an additional constraint on the lower redshift limit. In Figure 3 we illustrate this via an upper limit on the absolute flux (*black symbol*), which further suggests the source lies beyond  $z \simeq 6.6$ .

The NIRSPEC (McLean et al. 1998) observations were obtained with the Keck II telescope on the nights of 2003 May 10 and 11. The spectrograph was used in low-dispersion mode using a filter with transmission from 9500 to 11,200  $\text{\AA}$ . A slit width of  $0''.76$  was used to acquire the pair, giving a spectral resolution of  $R = 1100$ . We obtained 37 exposures of 900 s yielding a total integration time of 33 ks. We dithered along the slit between two different positions, verifying our pointing on a nearby reference star using the slit-viewing guide camera at each dither. These observations were also reduced using IRAF. Individual spectra were registered using offsets determined from simultaneous images obtained with the slit-viewing

<sup>7</sup> Although the weak NIRC  $J$  detection suggests a shallower UV slope, we give this discrepancy low weight in view of the superior quality of the *HST* data.

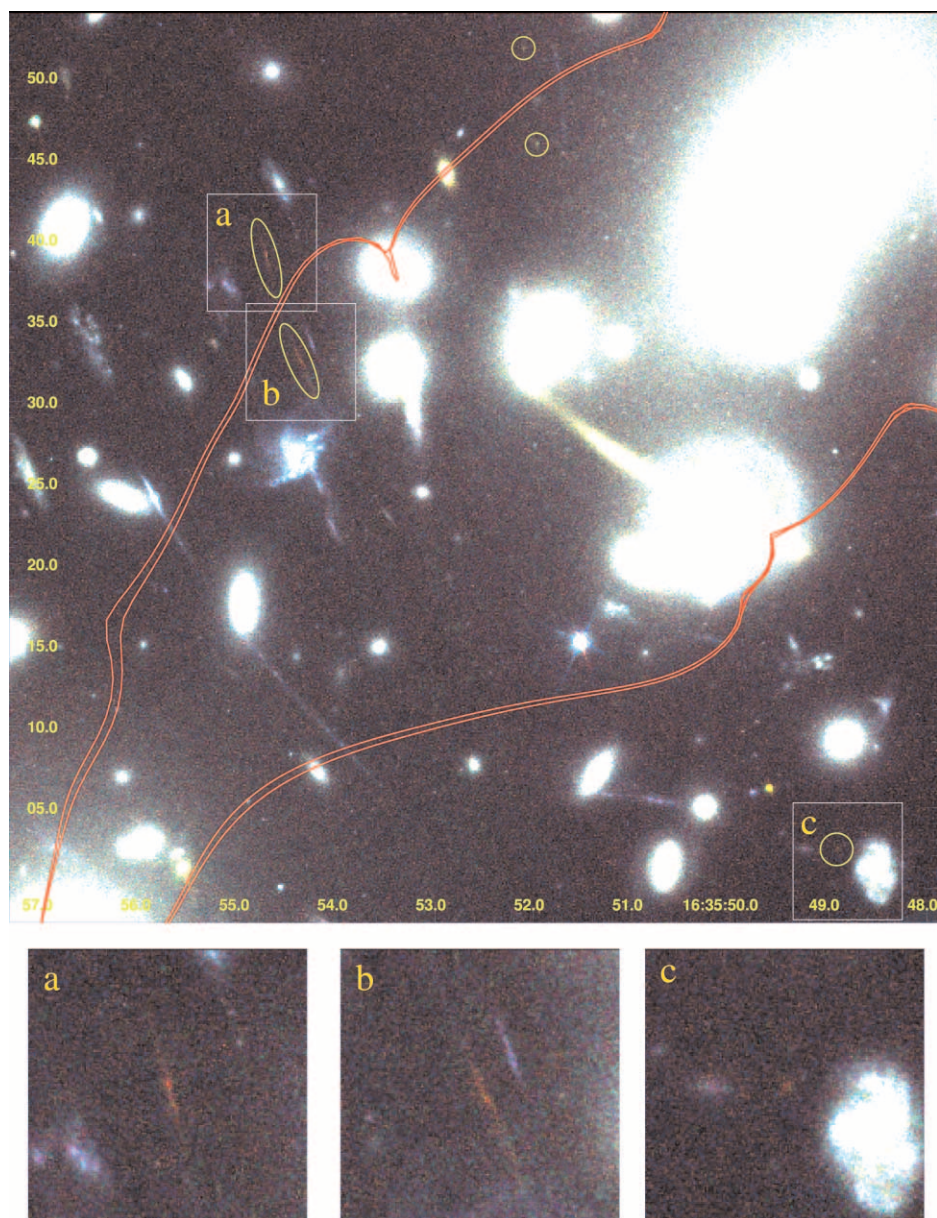


FIG. 2.—*Top*: Location of the image pair *a*, *b* and the third image *c* in a pseudocolor image made from the WFC2-F606W, F814W, and ACS-F850LP images. The red curves refers to the critical lines of infinite magnification for sources placed at  $z = 5.576$  and  $7.0$  in the context of the Kneib et al. (1996) mass model revised to include the  $z = 5.576$  pair (shown as unlabeled circles at the top of the figure) discussed by Ellis et al. (2001) and a triply imaged SCUBA source at  $z = 2.515$  (Kneib et al. 2004a). *Bottom*: Pseudocolor representation of the three images demonstrating their association with a single lensed source.

guide-camera. Our optimally combined spectrum of each image comprised 26 individual exposures, totaling an effective exposure time of 23 ks. All of the combined exposures were obtained in photometric conditions or through thin clouds. The data were flux-calibrated using observations of Feige 110 (Massey & Gronwall 1990), which provide an effective calibration from 9700 to 10,200 Å. Tests with two other standard stars (Feige 34 and Wolf 1346) indicate the relative flux calibration should be much more reliable than the absolute calibration; we have probably suffered from slit losses and possible absorption during the night because of faint cirrus. No emission lines were seen in the extracted NIRSPEC spectra, but a faint stellar continuum was detected for both images *a* and *b*; the signal is slightly stronger for image *a*.

Although observational selection plays an important role, as most successfully identified  $z > 5$  galaxies display intense

$\text{Ly}\alpha$  emission (Spinrad 2003), it is interesting to consider the maximum possible *observed* equivalent width,  $W_{\text{max}}$ , implied by our nondetections in the LRIS and NIRSPEC data. Using our spectrophotometric calibration, assuming a line width of 5 Å and a conservative  $5\sigma$  detection limit, Figure 4 shows  $W_{\text{max}}$  as a function of wavelength for our data. Although OH airglow emission precludes detection in a few small wavelength regions, for 60% of the important 9000–9500 Å interval an observed equivalent width larger than 120 Å (a value much less than for most high-redshift star forming sources; Hu et al 2003) would have been detected. From 9000–9300 Å ( $6.4 < z < 6.65$ ) and longward of 9550 Å ( $z > 6.85$ ) the constraint is tighter. Because of the much deeper exposures with NIRSPEC and the stronger continuum redward of 9800 Å, a more stringent  $5\sigma$  upper limit of  $W_{\text{max}} < 60$  Å is derived for the 9550–11,100 Å window,

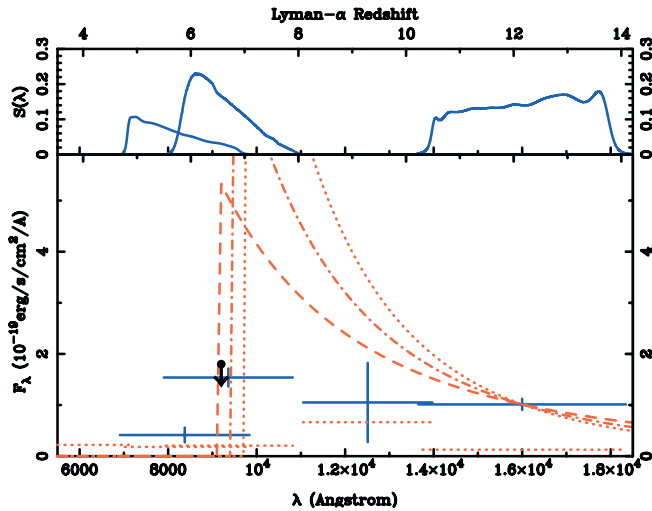


FIG. 3.—*Top*: Relative efficiencies of the filter+instrument used in our photometric observations. *From left to right*: WFPC2-F814W, ACS-F850LP, and NICMOS-F160W. *Bottom*: Spectral energy distribution of image *a* uncorrected for lensing magnification. Photometric points are indicated by blue crosses, and the  $3\sigma$  point source detection limits are indicated by horizontal dashed red lines below each data point. The nondetection of the continuum in the LRIS 9000–9300 Å window is indicated by the black arrow. Red dashed lines correspond to power-law SEDs [with  $f \propto \lambda^{-\alpha}$  for  $\lambda/(1+z) > 1216$  Å and  $f = 0$  otherwise] with slope indices (from bottom to top at  $1.2 \times 10^4$  Å) of  $\alpha = 3, 4,$  and  $5$ . The available data are consistent with a neutral hydrogen break in the interval 9250–9850 Å corresponding to  $6.6 < z < 7.1$ .

effectively ruling out any reasonable level of emission in the redshift range  $6.85 < z < 8.2$ . Thus, it seems reasonable to deduce that, *if the redshift is not in the  $6.65 < z < 6.85$  interval*, Ly $\alpha$  emission is either very weak or absent. It will be important in future, deeper, observations to rule out an

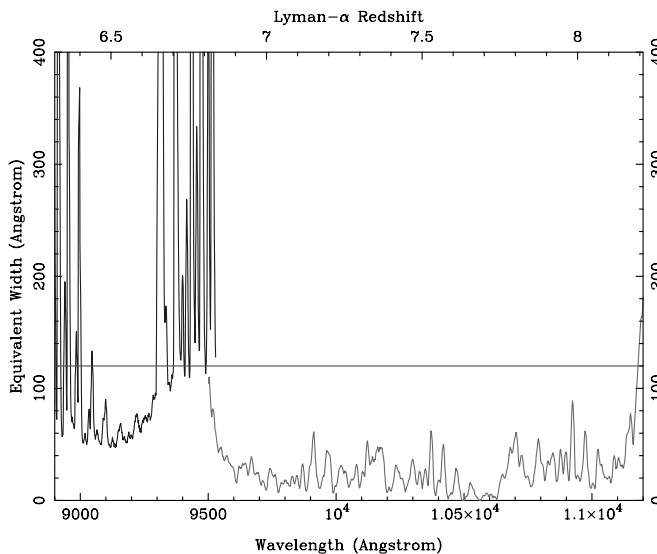


FIG. 4.—Observed equivalent width detection limit ( $5\sigma$ ),  $W_{\max}$ , for Ly $\alpha$  emission in the LRIS and NIRSPEC data assuming a line width of 5 Å. An emission line stronger than  $W = 120$  Å (horizontal line), corresponding to an integrated line flux of  $1.6 \times 10^{-18}$  ergs  $s^{-1}$   $cm^{-2}$  Å $^{-1}$ , would have been seen for 60% of the wavelength range 9000–9500 Å. Constraints in the range 9000–9300 Å and beyond 9550 Å are tighter. The longer NIRSPEC integrations provide a maximum equivalent width below  $W = 60$  Å for the entire 9550–11,100 Å range, corresponding to an integrated line flux of  $7 \times 10^{-19}$  ergs  $s^{-1}$   $cm^{-2}$  Å $^{-1}$ . [See the electronic edition of the Journal for a color version of this figure.]

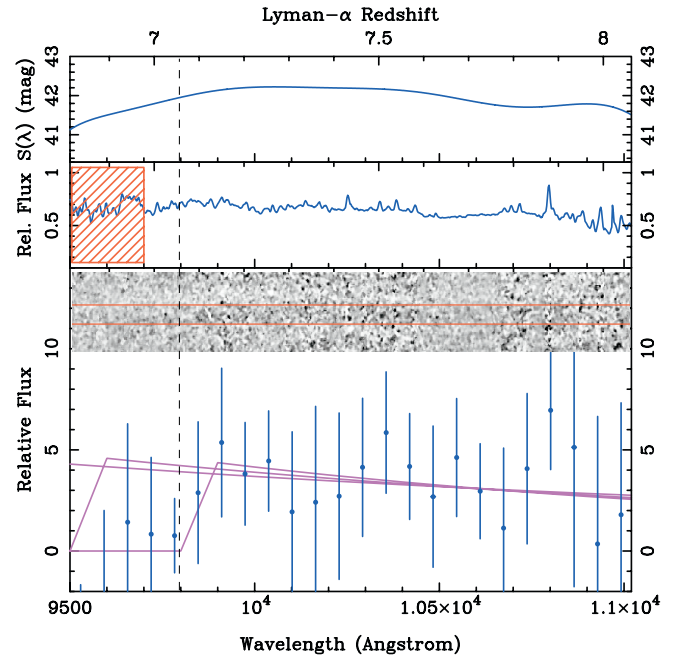


FIG. 5.—NIRSPEC spectrum for image *a* in the wavelength region 9500 Å– $1.1 \mu\text{m}$ . *Top*: Relative sensitivity of NIRSPEC in the configuration used derived from three independent flux calibration stars. Adequate sensitivity is available over the entire range. *Middle*: Observed spectrum of one of these standards, Feige 110 illustrating a priori the absence of any strong atmospheric features in the reduction. The red hatched rectangle indicates the region where variable atmospheric absorption is expected (Massey & Gronwall 1990). *Bottom*: Flux-calibrated binned spectrum for image *a*. Error bars include the effect of wavelength-dependent OH emission. Curves represent UV SEDs consistent with the photometry (Fig. 3) spanning the range  $6.6 < z < 7.1$ . The absence of significant flux below 9800 Å suggests a redshift at the upper end of this range, i.e.,  $z \sim 7$ .

emission line hiding in the OH forest at  $\sim 9500$  Å corresponding to a source at  $z \sim 6.8$ .

The absence of Ly $\alpha$  emission in a distant source may seem surprising. However, there are many examples of luminous Lyman break galaxies at lower redshift with weak or no emission (Shapley et al. 2003). Indeed, those authors claim only 20%–25% of star-forming examples show Ly $\alpha$  emission sufficiently prominent to be classified as narrowband excess objects.

The most important outcome of the long NIRSPEC exposure is the detection of a very faint continuum redward of 9800 Å (Fig. 5). A continuum signal is seen in both images. As it is stronger in image *a*, we will use this spectrum for the following analysis. Given the absence of Ly $\alpha$  emission and the inference of a photometric break in the wavelength range 9250–9850 Å, the key question is therefore the lowest wavelength at which a continuum signal can be seen in the NIRSPEC data.

Inspection of the data reveals a drop in the continuum flux at 9800 Å shortward of which there is no reliably detected signal despite a robust photometric calibration (see upper panels of Fig. 5). The OH spectrum is fairly clean in this region, although there is some atmospheric absorption that could affect the calibration at 9500–9700 Å. Although the feature itself is only marginal, the absence of flux below 9800 Å seems significant when one considers the photometric data summarized in Figure 3. Specifically, if the UV continuum extended down to 9250 Å, as would be the case if the source were at  $z = 6.6$ , it is difficult to understand why the stellar continuum is not detected to shorter wavelengths

(Fig. 5). Although this weak feature is the only indicator in our exhaustive attempts to measure a spectroscopic redshift, if it is indeed the cause of the Gunn-Peterson edge inferred from the photometric data, a redshift of  $z \simeq 7.05$  is implied. In this case, the photometric redshift analysis discussed in § 3.2 would indicate a steep UV continuum slope of  $\alpha = 5$ .

### 5. A $z \simeq 7$ SOURCE

Clearly identifying the redshift of this source has been extremely challenging, and further studies would be highly desirable to confirm our conclusions. We have introduced three independent arguments that, taken in combination, justify why the newly located multiple images arise via a single lensed source at a redshift  $z \sim 7$ . First, the geometrical configuration of images *a*, *b*, and *c* with respect to the critical line in this well-modeled cluster indicates  $z > 6$ . We argued that the location of the critical line in the vicinity of the pair is tightly constrained from the successful identification of the earlier source at  $z = 5.576$  (Ellis et al 2001). Second, there is a strong break indicated in the SED delineated by the broadband photometry extending from the F606W to F160W (*H*) filters, arguing for a redshift  $6.6 < z < 7.1$ . The lower redshift limit  $z > 6.6$  is particularly firm and supported by the absence of any LRIS continuum signal in the wavelength range 9000–9300 Å. Finally, the absence of any detectable signal below 9800 Å seen in the NIRSPEC continuum argues the redshift lies in the upper end of the photometric range,  $z \simeq 7$ , as otherwise the rising UV continuum would have been detected.

Even if one disregards the weak feature in the NIRSPEC spectrum, the  $6.6 < z < 7.1$  source is of considerable interest since, as we discussed in §§ 3–4, it is difficult to reconcile a spectral break at  $\lambda > 9250$  Å with a UV continuum slope of  $\alpha \lesssim 3$ , assuming the UV continuum is described by a power law above the Ly $\alpha$  discontinuity (Fig. 3). Starburst models assuming Population II metallicity and a Salpeter stellar initial mass function (IMF) typically produce slopes of  $\alpha \lesssim 2$  (Leitherer et al. 1999). Clearly, the inferred UV continuum of the  $z \sim 7$  source rises faster to shorter wavelengths than for any of the models calibrated with local data. Models based on massive metal-free stars, such as those that may be expected close to the epoch of reionization (Abel et al. 2000; Bromm et al. 1999), do produce somewhat steeper UV slopes,  $\alpha \simeq 3$  (Schaerer 2002). More precise photometry for this object, particularly in the 1–1.5  $\mu\text{m}$  range is needed to understand this issue. If a steep UV slope ( $\alpha \geq 3$ ) is indeed confirmed, the source may represent a promising candidate for a Population III starburst.

The star formation rate (SFR) of the source can be estimated from the stellar UV continuum luminosity. The unlensed F160W magnitude,  $H_{160W} = 26.5 \pm 0.1$ , translates into a specific flux of  $2.35 \times 10^{-31}$  ergs s $^{-1}$  cm $^{-2}$  Hz $^{-1}$  at 1.6  $\mu\text{m}$ , assuming a smooth SED. The intrinsic specific luminosity at 2000 Å is then  $1.85 \times 10^{28}$  ergs s $^{-1}$  Hz $^{-1}$ , implying an SFR of  $2.6 M_{\odot}$  yr $^{-1}$  using the Kennicutt (1998) empirical calibration. We estimate a 15% error arising from uncertainties in the photometry and magnification. This derived SFR is significantly higher than that for the  $\simeq 0.5 M_{\odot}$  yr $^{-1}$  computed for the lensed source at  $z = 5.576$  (Ellis et al. 2001) but within the range of typical Ly $\alpha$  emitters at  $z \simeq 5.5$ –6.5.

Our estimated SFR may suffer from two systematic errors. If dust is present, it will dim the UV continuum, causing us to underestimate the value. However, assuming a familiar selective extinction curve, reddening would then imply the intrinsic UV continuum slope is even steeper than  $\alpha \simeq 3$ –5.

A second uncertainty arises from our assumed stellar IMF and metallicity via Kennicutt’s local calibration. If the IMF is top-heavy or the metallicity is lower than in local starbursts, the SFR will likely have been overestimated.

Given the intense star formation, the apparent lack of Ly $\alpha$  emission is puzzling if dust extinction is not important. Weak or absent Ly $\alpha$  emission seen in the younger (<1 Gyr) Lyman break galaxies at  $z \simeq 3$  has been interpreted via the presence of dust shrouds that are eventually disrupted via feedback processes as the stellar population matures (Shapley et al. 2003). As our source is likely younger than 500 Myr, a very specific dust/gas geometry would be needed to strongly extinct the Ly $\alpha$  photons without reddening the UV continuum. This problem may be exacerbated if the IMF is top-heavy or the metallicity low, since the ionizing photon production rate will be higher, making any emission line yet more prominent (see Malhotra & Rhoads 2002).

An alternative explanation for the absence of Ly $\alpha$  emission may be incomplete reionization at  $z \simeq 7$ . Neutral hydrogen can scatter Ly $\alpha$  photons after they have escaped the interstellar medium of the emitting galaxy (e.g., Miralda-Escude & Rees 1998). If the source were embedded in a neutral zone, even a strong Ly $\alpha$  emission line emitted from the galaxy could be quenched. However, in such cases, simulations suggest that emission can still be observed even from sources embedded in fully neutral zones, depending on details of the many relevant parameters of the source (Haiman 2002; Santos 2004).

Since the universe is only 750 Myr old at  $z = 7$ , the total stellar mass is unlikely to exceed  $(1\text{--}2) \times 10^9 M_{\odot}$ . Halos of mass greater than  $1.2 \times 10^{10} M_{\odot}$  at  $z \simeq 7$  are quite consistent with conventional structure formation models (Barkana & Loeb 2002) and sufficient to supply baryons to sustain the observed SFR. The instantaneous baryonic accretion rate for such a halo at  $z = 7$  is, on average,  $4.4 M_{\odot}$  yr $^{-1}$  (e.g., Lacey & Cole 1993), so even if an earlier starburst consumed most of the baryons, they can be rapidly replenished. Although we have no constraints on the actual star formation history, these arguments emphasize that we are not necessarily viewing the system at a special time in its evolution.

The strong magnification ( $\simeq 25$  times) of the two brighter images gives us our first glimpse into the morphological structure of a very distant source on subkiloparsec scales. Both images *a* and *b* have a bright core, a second fainter knot, and extended emission of lower surface brightness (Fig. 1). There is no noticeable color gradient. Our mass model for A2218 implies magnifications of  $\sim 15$  times along the major axis of images *a* and *b*, and  $\sim 1.7$  times along the minor axis. The  $0''.15$  width of the F850LP point-spread function translates into a physical resolution of  $\sim 470$  pc along the minor axis and  $\sim 50$  pc along the major axis.

We thus infer that the source (observed with  $3''.6 \times < 0''.15$ ) has a maximum physical size of 1.2 kpc by less than 500 pc. The maximal associated area of 0.6 kpc $^2$  indicates a star formation surface density in excess of  $4.3 M_{\odot}$  yr $^{-1}$  kpc $^{-2}$ . The bright knot is only 100 pc across, implying a star formation surface density in the range  $\sim 50$ –250  $M_{\odot}$  yr $^{-1}$  kpc $^{-2}$  depending on the exact geometry, comparable to the most intense starburst activity observed locally (Kennicutt 1998).

If this source is typical of those that reionized the universe in a narrow time interval of  $\Delta z = 1$  around  $z \simeq 7$ , we can estimate the expected surface density from the arguments presented by Stiavelli et al. (2004). Depending on the source temperature, Lyman continuum escape fraction, and

clumpiness of the intergalactic medium, we would deduce that surface densities  $n \simeq 0.3\text{--}5 \text{ arcmin}^{-2}$  are necessary. In as much as it is possible to estimate the actual surface density from one source and the limited area examined by looking through only one cluster lens to find it, we find a number density of  $n \simeq 1 \pm 0.5 \text{ arcmin}^{-2}$ .

In conclusion, we present evidence that we have found a highly magnified source that lies beyond  $z \simeq 6.6$ , possibly at  $z \simeq 7$ . Even in advance of the infrared capabilities of the *James Webb Space Telescope*, further observation of this source will be important in determining a more secure redshift and improving the constraints on the slope of the UV continuum. Further spectroscopy in the  $9200 \text{ \AA} - 1 \mu\text{m}$  region would be valuable to probe any  $\text{Ly}\alpha$  emission at  $z \simeq 6.8$  (Fig. 4) and to confirm (or otherwise) the significance of the weak continuum drop seen in the NIRSPEC data at  $9800 \text{ \AA}$ . The location of the Gunn-Peterson trough might also be verified more precisely via narrowband imaging through gaps in OH forest and with a deep ACS grism spectroscopy.

Notwithstanding the need for further work and regardless of its precise redshift in the constrained window  $6.6 < z < 7.1$ , our source appears to be a star-forming galaxy with intriguing spectral properties, possibly representative of a new population responsible for ending cosmic reionization. While our discovery highlights many of the challenges facing searches for those  $z > 6.5$  galaxies responsible for reionization, it also demonstrates the ability of strong lensing by clusters of galaxies to locate and reveal the detailed properties of high-redshift sources. The lensed galaxy presented in this paper, if observed unlensed at  $z_{\text{AB}} \sim 28.5$ , would lie at the detection

limit of the upcoming UDF observation,<sup>8</sup> and no spectroscopic follow-up would have been possible.

We thank Fred Chaffee for his continued encouragement to track down the nature of this intriguing system, and we acknowledge useful discussions with Bob Abraham, Chris Conselice, Graham Smith, Mark Sullivan, and Tommaso Treu. Hy Spinrad and Andy Bunker are thanked for reading an earlier version of this manuscript and offering valuable suggestions. We thank two anonymous referees for their valuable comments that significantly improved the presentation of our data. We thank Alice Shapley and Dawn Erb for helpful advice on the optimum procedures for obtaining and reducing faint NIRSPEC data. We also thank James Larkin and James Graham for their advice concerning the use of NIRSPEC in the  $1 \mu\text{m}$  wavelength region. Andrew Blain and Naveen Reddy kindly provided access to the Keck NIRC observations. Faint object spectroscopy at the Keck observatory is made possible through the dedicated efforts of Ian McLean and collaborators for NIRSPEC, and Judy Cohen, Bev Oke, Chuck Steidel, and colleagues at Caltech for LRIS. J. P. K. acknowledges support from Caltech and CNRS. M. R. S. acknowledges the support of NASA GSRP grant NGT5-50339. The study of A2218 as a cosmic lens is supported by NASA STScI grant HST-GO-09452.01-A.

<sup>8</sup> See <http://www.stsci.edu/hst/udf/parameters>.

#### REFERENCES

- Abel, T., Bryan, G. L., & Norman, M. L. 2000, *ApJ*, 540, 39  
 Barkana, R., & Loeb, A. 2002, *ApJ*, 578, 1  
 Becker, R. H., et al. 2001, *AJ*, 122, 2850  
 Bouwens, R. J., et al. 2003, *ApJ*, 595, 589  
 Bromm, V., Coppi, P. S., & Larson, R. B. 1999, *ApJ*, 527, L5  
 Dickinson, M., et al. 2004, *ApJ*, 600, L99  
 Djorgovski, S. G., Castro, S. M., Stern, D., & Mahabal, A. A. 2001, *ApJ*, 560, L5  
 Ellis, R. S., Santos, M. R., Kneib, J-P, & Kuijken, K. 2001, *ApJ*, 560, L119  
 Fan, X., et al. 2002, *AJ*, 123, 1247  
 Haiman, Z. 2002, *ApJ*, 576, L1  
 Hu, E. M., Cowie, L. L., McMahon, R. G., Capak, P., Iwamuro, F., Kneib, J.-P., Maihara, T., & Motohara, K. 2002, *ApJ*, 568, L75  
 Hu, E. M., Cowie, L. L., & McMahon, R. G. 1998, *ApJ*, 502, L99  
 Kennicutt, R. C. 1998, *ARA&A*, 36, 189  
 Kneib, J.-P., Ellis, R. S., Smail, I. R., Couch, W. J., & Sharples, R. M. 1996, *ApJ*, 471, 643  
 Kneib, J.-P., van der Werf, P., Knudsen, K., Smail, I., Blain, A., Frayer, D., Barnard, V., & Ivison, R. 2004, *MNRAS*, in press  
 Kodaira, K., et al. 2003, *PASJ*, 55, L17  
 Kogut, A., et al. 2003, *ApJS*, 148, 161  
 Lacey, C. & Cole, S. 1993, *MNRAS*, 262, 627  
 Leitherer, C., Schaerer, D., & Goldader, J. D. 1999, *ApJS*, 123, 3  
 Malhotra, S., & Rhoads, J. E. 2002, *ApJ*, 565, L71  
 Malhotra, S., Rhoads, J., Dey, A., Stern, D., & Spinrad, H. 2001, in *ASP Conf. Ser. 240, Gas and Galaxy Evolution*, ed. J. E. Hibbard, J. E., M. Rupen, & J. H. van Gorkom (San Francisco: ASP), 97  
 Massey, P., & Gronwall, C. 1990, *ApJ*, 358, 344  
 McLean, I. S., et al. 1998, *Proc. SPIE*, 3354, 566  
 Miralda-Escude, J., & Rees, M. J. 1998, *ApJ*, 497, 21  
 Oke, J. B., et al. 1995, *PASP*, 107, 375  
 Santos, M. R. 2004, *MNRAS*, in press (astro-ph/0308196)  
 Santos, M. R., Ellis, R. S., Kneib, J-P, Richard, J., & Kuijken, K. 2004, *ApJ*, 606, 683  
 Schaerer, D. 2002, *A&A*, 382, 28  
 Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65  
 Spergel, D. N., et al. 2003, *ApJS*, 148, 175  
 Spinrad, H. 2003, in *Astrophysics Update*, ed. J. Mason (Berlin: Springer), in press (astro-ph/0308411)  
 Spinrad, H., Stern, D., Bunker, A., Dey, A., Lanzetta, K., Yahil, A., Pascarella, S., & Fernandez-Soto, A. 1998, *AJ*, 116, 2617  
 Stanway, E., Bunker, A., McMahon, R., Ellis, R. S., Treu, T., & McCarthy, P. 2004, *ApJ*, in press (astro-ph/0308124)  
 Stern, D., & Spinrad, H. 1999, *PASP*, 111, 1475  
 Stiavelli, M., Fall, S. M., & Panagia, N. 2004, *ApJ*, 600, 508  
 Yan, H., Windhorst, R. A., & Cohen, S. H. 2003, *ApJ*, 585, L93