

## A FAINT STAR-FORMING SYSTEM VIEWED THROUGH THE LENSING CLUSTER ABELL 2218: FIRST LIGHT AT $z \approx 5.6$ ?<sup>1</sup>

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### ABSTRACT

We discuss the physical nature of a remarkably faint pair of Ly $\alpha$ -emitting images discovered close to the giant cD galaxy in the lensing cluster Abell 2218 ( $z = 0.18$ ) during a systematic survey for highly magnified star-forming galaxies beyond  $z = 5$ . A well-constrained mass model suggests the pair arises via a gravitationally lensed source viewed at high magnification. Keck spectroscopy confirms the lensing hypothesis and implies that the unlensed source is a very faint ( $I \sim 30$ ), compact ( $<150 h_{65}^{-1}$  pc), and isolated object at  $z = 5.576$  whose optical emission is substantially contained within the Ly $\alpha$  emission line; no stellar continuum is detectable. The available data suggest the source is a promising candidate for an isolated  $\sim 10^6 M_{\odot}$  system seen producing its first generation of stars close to the epoch of reionization.

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

### 1. INTRODUCTION

Exploring the era when the first stars formed by locating high-redshift sources with demonstrably young cosmic ages represents the next outstanding challenge for observational cosmology (Mather & Stockman 2000). Although luminous quasars (Zheng et al. 2000; Fan et al. 2000, 2001) and star-forming galaxies (Dey et al. 1998; Weymann et al. 1998; Spinrad et al. 1998; Hu, McMahon, & Cowie 1999) have been located beyond  $z \approx 5$ , to be detected these must be spectacularly luminous and rare examples drawn from a largely unknown underlying population (for an excellent review of attempts to find very distant galaxies, see Stern & Spinrad 1999).

Gravitational magnification by foreground clusters of galaxies, whose mass distributions are constrained by arcs and multiple images of known redshift, has already provided new information on the abundance of faint background objects (Kneib et al. 1996). Particularly high magnifications (approximately times 40) are expected in the *critical regions*, which can be located precisely in well-understood clusters for sources occupying specific redshift ranges, e.g.,  $2 < z < 7$ . Although the volumes probed in this way are smaller than those addressed in panoramic narrowband surveys (Hu, Cowie, & McMahon 1998; Malhotra et al. 2001), intrinsically much fainter and most likely more representative sources are sampled. If the surface density of such sources is sufficient, this may be a promising route for securing the first glimpse of young cosmic sources beyond  $z \approx 5$ .

Accordingly, we have begun a blind spectroscopic survey of the appropriate critical lines of several well-constrained lensing clusters with *Hubble Space Telescope* (HST) images

(M. R. Santos, R. S. Ellis, K. Kuijken, & J.-P. Kneib 2001, in preparation). Briefly, our strategy involves undertaking long-slit scans of regions  $7'' \times 120''$  in extent with the Keck I Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995), using gratings that offer a spectral resolution  $\approx 4 \text{ \AA}$  in the OH forest and  $\approx 6 \text{ \AA}$  in the blue. The typical wavelength range covered is 3500–9350  $\text{\AA}$ , offering the potential of seeing lensed Ly $\alpha$  sources in the important range  $2 < z_s < 7$ . With a  $1''.0$  slit, the dwell at each location is normally  $2 \times 1000$  s.

In the course of surveying the cluster Abell 2218 ( $z = 0.18$ ) on 2001 April 23, we encountered a strong emission line at 7989  $\text{\AA}$  close to the central cD (Figs. 1 and 2). Astrometry associates this emission with a faint, marginally resolved source in the early release Wide Field Planetary Camera 2 (WFPC2) F814W image (labeled “a” in Fig. 1) with  $I_{814} = 25.9 \pm 0.2$ . Inspection of the Kneib et al. (1996) mass model suggests that a second image with  $I_{814} \approx 26.0 \pm 0.3$ ,  $6''$  away (“b” in Fig. 1), represents a counterimage of the same highly magnified  $z > 5$  source.

On 2001 May 21, we used the Keck II Echelle Spectrograph and Imager (ESI; Scheinis et al. 2000) at a higher spectral resolution ( $\approx 1.25 \text{ \AA}$ ) with a  $0''.75$  slit aligned to include both images (see inset in Fig. 1). With  $2 \times 2000$  s exposures, strong emission was confirmed from *both* images (Fig. 3, *left*). The spectra are identical (to within the signal-to-noise ratio), confirming the lensing hypothesis. Importantly, the magnitude difference in the emission lines ( $\Delta m_{\text{line}} \approx 0.2 \pm 0.1$ ) is comparable to that in the  $I_{814}$  photometry. The combined flux-calibrated spectrum (Fig. 3*b*) reveals a single emission line with an asymmetric (P Cygni–like) profile suggestive of gas outflow.

The location and separation of the images was already suggestive of lensing of a high-redshift source consistent with emission arising from Ly $\alpha$  at  $z = 5.576$  (corresponding to the peak in the combined spectrum at 7996  $\text{\AA}$ ).<sup>6</sup> Were the emission to arise from H $\alpha$ , the images would have to be a physically associated pair just behind the cluster, and the absence of other emission would be puzzling given the extensive LRIS wavelength coverage. The most plausible alternative to Ly $\alpha$  for a lone emission line would be [O II] at  $z = 1.14$ . This can be eliminated not only by lensing arguments (cf. the location of

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<sup>6</sup> This redshift is presumably a slight overestimate by an unknown amount given the likelihood of self-absorption.

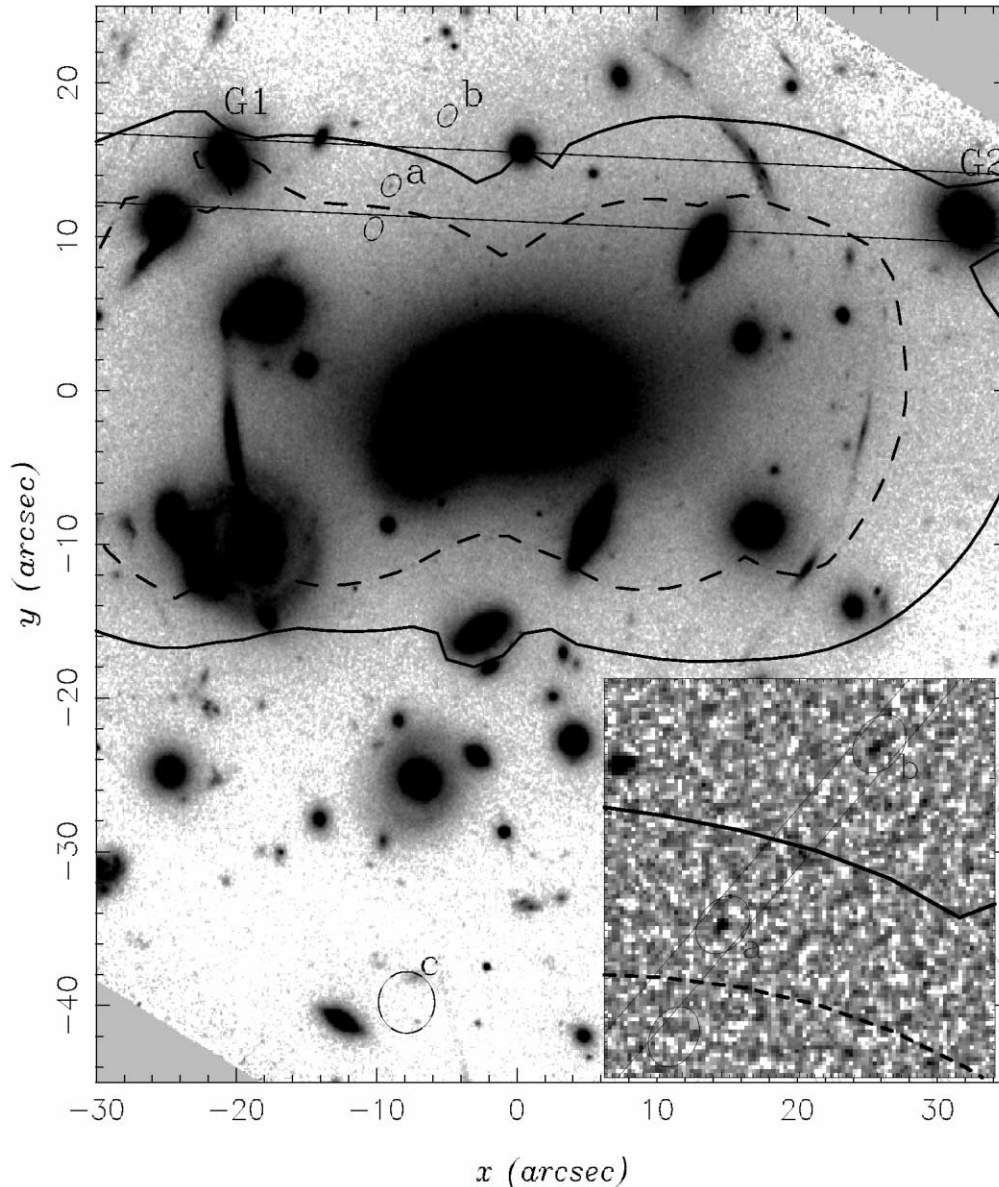


FIG. 1.—*HST* F814W image of Abell 2218 ( $z = 0.18$ ) with the location of the LRIS long-slit scanning region marked. Images *a* and *b* represent the lensed pair at  $z = 5.576$ ; the inset ( $10'' \times 10''$ ) illustrates the secondary spectroscopic configuration adopted with ESI. Curves refer to critical lines of infinite magnification for a source at  $z = 1.14$  (dashed curve) and 5.576 (solid curve) in the context of the Kneib et al. (1996) mass model. For a source at  $z = 1.14$ , the counterimage of *a* would lie just below the appropriate critical line (small circle) and is not seen. The large circle *c* refers to the region where a much fainter ( $I \sim 29$ ) third image is expected for a source at  $z = 5.576$ .

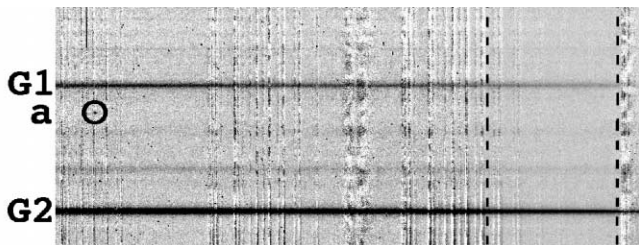


FIG. 2.—Discovery of an emission-line source close to the cD in the rich cluster Abell 2218. Keck I LRIS-R spectral image of a region  $100''$  in extent covering  $7900\text{--}9350 \text{ \AA}$  with the emission line attributed to object *a* at  $7989 \text{ \AA}$  marked. The dashed lines at longer wavelengths refer to the wavelength range used to deduce a statistical upper limit on a stellar continuum from the source (see text). The spectra of fiducial cluster galaxies G1 and G2 labeled in Fig. 1 are marked.

the critical lines and image configurations expected in Fig. 1) but also by the fact the  $[\text{O II}] \lambda\lambda 3726, 3728$  doublet would be readily resolved at the spectral resolution of ESI.

## 2. SOURCE PROPERTIES

The remarkable features of the  $z = 5.576$  source are its faintness (particularly considering the high magnification afforded by its proximity to the critical line), its small angular size in the *HST* image, and the apparent absence of any stellar continuum in both the LRIS and ESI spectra.

The magnification of the two images in the Figure 1 inset can be determined from the Abell 2218 mass model (Kneib et al. 1996), which has been extensively tested via spectroscopy of 18 arclets by Ebbels et al. (1998). In this model, the mag-

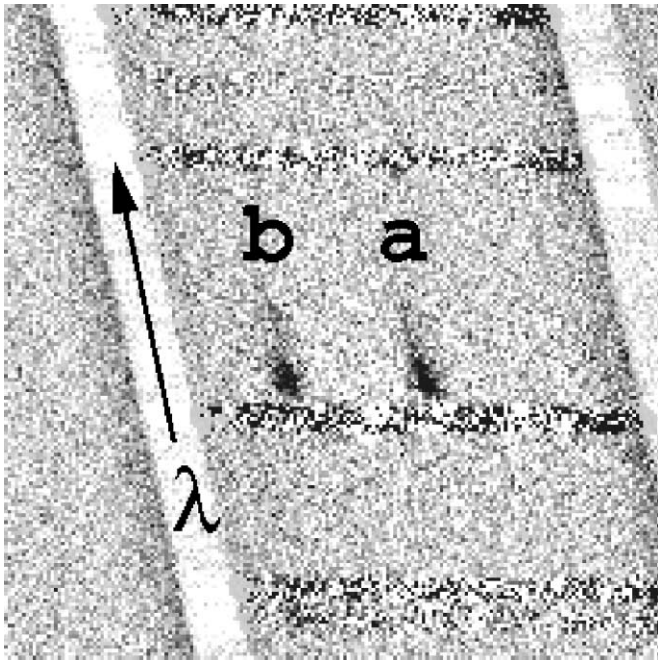
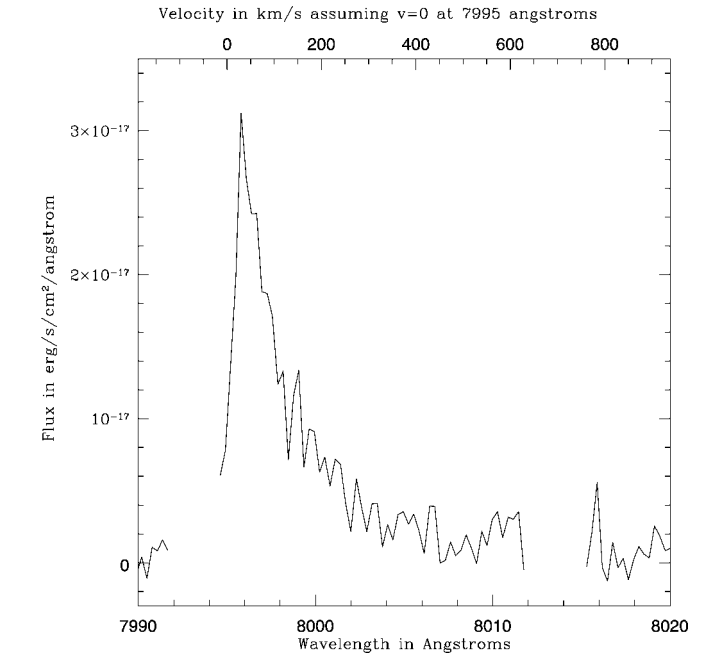


FIG. 3.—Confirmation of strong emission in the pair of images marked in Fig. 1 using the Keck II ESI. *Left*: Two-dimensional sky-subtracted spectral image using the 20" slit. *Right*: Flux-calibrated spectrum of the region around Ly $\alpha$  emission combined from both images revealing a P Cygni-like profile extending redward by  $\approx 200$  km s $^{-1}$  in the rest frame. The redshift corresponding to the peak emission is  $z = 5.576$ .

nifications for sources *a* and *b* are, respectively, 3.8 mag ( $\times 33.1$ ) and 3.7 mag ( $\times 30.2$ ), implying a (unlensed) source magnitude of  $I_{814} \approx 29.7$ . Inspection of the dithered WFPC2 image indicates that image *a* is marginally resolved along the shear direction (i.e., toward the other image). The appropriate half-light scales are  $0''.23 \times <0''.15$ . Allowing for the *HST* resolution and the linear magnification at this point in the cluster's gravitational field implies a physical diameter of less than  $150 h_{65}^{-1}$  pc.<sup>7</sup>

The lensing model also offers insight into the crucial question of whether we are witnessing magnification of an isolated object or a star-forming component (e.g., an H II region) embedded in a more extended source close to a caustic. The mass model indicates that the source that produces the pair lies 1.2 kpc from the caustic. Thus, any comparable emitting region (containing line or continuum flux) within this distance would also be highly magnified and possibly detected. Together with the remarkably small physical size, this suggests the source is a truly isolated system and not, for example, a star-forming subcomponent of a larger luminous system (cf. Franx et al. 1997; Trager et al. 1997).

A substantial component of the broadband *I*-band flux arises from the line emission, suggesting that the stellar continuum



is unusually faint. If the F814W flux were produced by a single emission line at  $\lambda 7989$ , the flux density in the line would be  $F_a(HST) = (1.2 \pm 0.2) \times 10^{-16}$  ergs cm $^{-2}$  s $^{-1}$ . This is only 70% higher than the mean inferred from the ESI spectra, corrected for extinction:  $F_a(ESI) = (6.8 \pm 0.7) \times 10^{-17}$  ergs cm $^{-2}$  s $^{-1}$ . The ESI line flux is consistent, within uncertainties of absolute calibration, with that inferred for image *a* in the LRIS data:  $F_a(LRIS) = (5.6 \pm 0.5) \times 10^{-17}$  ergs cm $^{-2}$  s $^{-1}$ .

Limits on any stellar continuum flux can be explored further in the LRIS wavelength region  $\lambda\lambda 9020$ – $9297$ , which is relatively free from OH contamination (Fig. 2). Including the noise across the LRIS slit at this location, we deduce a  $3\sigma$  upper limit to the continuum flux of  $3 \times 10^{-20}$  ergs cm $^{-2}$  s $^{-1}$   $\text{\AA}^{-1}$ . Assuming a flat spectrum longward of Ly $\alpha$ , this upper limit integrated over the F814W bandpass would also yield a signal comparable to the emission-line flux.

Limited near-infrared data is available for Abell 2218 from commissioning data taken with the INGRID infrared camera on the 4.2 m William Herschel Telescope (WHT; supplied by courtesy of I. Smail). Image *a* remains undetected to limits of  $J = 22.5$  and  $K = 21.5$  ( $5\sigma$  for a point source). At respective rest-frame wavelengths,  $\lambda \approx 1600$  and  $3350$   $\text{\AA}$ , neither filter is likely to be contaminated by strong emission lines. These nondetections give further constraints on the continuum flux, viz.,  $F_a(J) < 3.9 \times 10^{-19}$  ergs cm $^{-2}$  s $^{-1}$   $\text{\AA}^{-1}$  and  $F_a(K) < 9.8 \times 10^{-20}$  ergs cm $^{-2}$  s $^{-1}$   $\text{\AA}^{-1}$ .

We summarize the properties of the source detected in Abell 2218 in Table 1. Although our observed line flux is comparable to those in sources seen at lower redshift in narrowband searches (Hu et al. 1998), when lensing is taken into account the true source flux is much fainter.

### 3. FIRST LIGHT?

We now address the interesting question of whether the source lensed by Abell 2218 is being observed at a special time in its history, perhaps consistent with its first generation

<sup>7</sup> We assume a cosmological model with  $\Omega_M = 0.3$  and  $\Omega_\Lambda = 0.7$  throughout.

TABLE 1  
UNLENSED SOURCE FLUXES

Data Set	Total (mag)	Continuum <sup>a</sup>	Ly $\alpha$ <sup>b</sup>
<i>HST</i> /WFPC2 F814W .....	29.7	$<2.4 \times 10^{-20}$	$<3.6 \pm 0.6$
LRIS .....	...	$<6 \times 10^{-21}$	$1.7 \pm 0.2$
ESI .....	...	...	$2.1 \pm 0.2$
WHT <i>J</i> .....	$>26.3$	$<8 \times 10^{-20}$	...
WHT <i>K</i> .....	$>25.3$	$<2 \times 10^{-20}$	...

<sup>a</sup>  $3\sigma$  upper limits on the continuum flux per unit wavelength in the rest frame. In units of ergs cm $^{-2}$  s $^{-1}$   $\text{\AA}^{-1}$ .

<sup>b</sup> In units of  $10^{-18}$  ergs cm $^{-2}$  s $^{-1}$ .

of stars. Although the Ly $\alpha$  line is an unreliable guide to the ongoing star formation rate (SFR) because of self-absorption, scattering, and dust extinction difficulties, we argue that uncertainties arising from this diagnostic most likely strengthen our conclusions.

Adopting the relationship  $1 M_{\odot} \text{ yr}^{-1} = 1.5 \times 10^{42} \text{ ergs s}^{-1}$  in Ly $\alpha$  (Ferland & Osterbrock 1985; Osterbrock 1989; Kennicutt 1998) and including a magnification of 33 with a 100% escape fraction and zero extinction, we infer a current SFR of  $0.5 M_{\odot} \text{ yr}^{-1}$ . We consider this a lower limit given the conservative assumptions above. Although our physical scale of less than 150 pc is comparable to that resolved for 30 Doradus in the Large Magellanic Cloud (Scowen et al. 1998), the SFR is over an order of magnitude larger than the integrated value for energetic giant H II regions contained within nearby star-forming galaxies (McKee & Williams 1997). Consistent with its isolated nature, the source appears to be a very powerful extragalactic H II region with a luminosity  $L_{\alpha} \approx 10^{42} \text{ ergs s}^{-1}$  (cf. Melnick, Terlevich, & Terlevich 2000).

At  $z = 5.576$ , in our adopted cosmology, the cosmic age is only 1 Gyr. We ran the STARBURST99 code (Leitherer, Schaerer, & Goldader 1999) for a metal-poor ( $Z = 10^{-3}$ ) system with a constant SFR of  $0.5 M_{\odot} \text{ yr}^{-1}$  in order to explore at what age a detectable stellar continuum would emerge in the LRIS spectral window ( $\lambda_{\text{UV}} = \lambda_{\text{rest}} = 1370\text{--}1415 \text{ \AA}$ ). Ignoring dust extinction, this provides a tighter constraint than the same calculation applied to the  $J$ - and  $K$ -band limits at their longer rest wavelengths. For our adopted upper limit of  $F_{\text{UV}} < 3 \times 10^{-20} \text{ ergs cm}^{-2} \text{ \AA}^{-1}$  (see § 2), the appropriate unlensed continuum luminosity,  $L_{\text{UV}} < 2 \times 10^{39} \text{ ergs s}^{-1} \text{ \AA}^{-1}$ , would be exceeded at the observed SFR in less than 2 Myr, suggesting the object could be remarkably young with a stellar mass  $\sim 10^6 M_{\odot}$ .

If the SFR were higher in the past, or if the Ly $\alpha$  emission were subject to upward corrections due to self-absorption, the implied age for the continuum flux limit would be even shorter. Although we cannot yet provide any observable constraints on dust extinction, given the Ly $\alpha$  line is more likely to be suppressed than the adjacent continuum, this would also imply that we have *overestimated* the age and implied stellar mass.

#### 4. DISCUSSION

Hierarchical models of structure formation predict a high density of systems undergoing their first era of star formation

at  $z \approx 6$  (Haiman & Spaans 1999). Our critical line survey (M. R. Santos, R. S. Ellis, K. Kuijken, & J.-P. Kneib 2001, in preparation) will provide new constraints on their abundance and redshift distribution out to  $z \approx 7$ . In particular, the example discussed here could not have been detected without the lensing boost afforded by Abell 2218. Its unlensed equivalent would not have been reliably detected even in the Hubble Deep Field.

The most interesting suggestion arising from our study is the possible young age inferred from our upper limit on the stellar continuum in the context of the SFR deduced from the Ly $\alpha$  flux. While there are many uncertainties in this deduction, we argue that they work in the sense of strengthening the conclusion. If our upper age limit is correct, very deep infrared imaging would be needed to reliably probe the spectral energy distribution of this source longward of  $1 \mu\text{m}$ , i.e., in the rest-frame optical. Depending on the star formation history, lensed  $2 \mu\text{m}$  fluxes of 50 nJy ( $K \approx 25$ ) are expected. An unlensed analog would have a flux density of only 1 nJy and would clearly be challenging even for the *Next Generation Space Telescope*.

H II regions of stellar mass of order  $10^6 M_{\odot}$  with SFRs  $\approx 1 M_{\odot} \text{ yr}^{-1}$  can be found at lower redshifts. The significance of the system in Abell 2218 lies in the fact that an isolated, possibly young, low-mass system has been located close to the redshift at which many now believe reionization may be occurring (Djorgovski et al. 2001; Becker et al. 2001). Just as with those constraints that sample a few (possibly atypical) sight lines to a distant quasar, so the stellar history of further examples of our star-forming source, located with the aid of strong lensing, will provide an early census of such systems beyond  $z \approx 5$ .

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