A Faint Star-Forming System Viewed Through the Lensing Cluster Abell 2218: First Light at $z \simeq 5.6$?

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ABSTRACT

We discuss the physical nature of a remarkably faint pair of Lyman α-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 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 Lyman α 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.[1]

Subject headings: cosmology: observations, galaxies: formation, galaxies: evolution, 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 et al 1999) have been located beyond $z \simeq 5$, 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 ($\simeq \times 40$) 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 narrow band surveys (Hu et al 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 $z \simeq 5$.

Accordingly, we have begun a blind spectroscopic survey of the appropriate critical lines of several well-constrained lensing clusters with Hubble Space Telescope images (Santos et al 2001). Briefly, our strategy involves undertaking long-slit scans of regions 7 × 120 arcsec in extent with the Keck I Low Resolution Imaging Spectrograph (LRIS, Oke et al 1995), using gratings that offer a spectral resolution of $\simeq$4 Å in the OH forest and $\simeq$6 Å in the blue. The

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[1]Using data obtained with the Hubble Space Telescope operated by AURA 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.

typical wavelength range covered is $\lambda\lambda 3500$-9350 Å offering the potential of seeing lensed Ly α sources in the important range $2 < z_s < 7$. With a 1.0 arcsec slit, the dwell at each location is normally 2×1000sec.

In the course of surveying the cluster Abell 2218 (z=0.18) on 23 April 2001 we encountered a strong emission line at $\lambda 7989$ Å close to the central cD (Figures 1 and 2). Astrometry associates this emission with a faint, marginally-resolved, source in the Early Release WFPC2 F814W image (labelled a in Figure 1) with I_{814}=25.9 $\pm$ 0.2. Inspection of Kneib et al's (1996) mass model suggests that a second image with $I_{814} \simeq 26.0 \pm 0.3$, 6 arcsec away ($b$ in Figure 1), represents a counter-image of the same highly magnified $z > 5$ source.

On May 21, 2001 we used the Keck II Echelle Spectrograph and Imager (ESI, Scheinis et al 2000) at a higher spectral resolution ($\simeq 1.25$ Å) with a 0.75 arcsec slit aligned to include both images (see inset panel in Figure 1). With 2×2000 sec exposures, strong emission was confirmed from *both* images (Figure 3a). The spectra are identical (to within the signal/noise) confirming the lensing hypothesis. Importantly, the magnitude difference in the emission lines ($\Delta m_{line} \simeq 0.2 \pm 0.1$) is comparable to that in the I_{814} photometry. The combined flux-calibrated spectrum (Figure 3b) 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 Lyα at z=5.576 (corresponding to the peak in the combined spectrum at $\lambda 7996$ Å [2]). Were the emission to arise from $H\alpha$, the images 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 Lyα for a lone emission line would be [O II] at z=1.14. This can be eliminated not only by lensing arguments (c.f. the location of the critical lines and image configurations expected in Figure 1), but also by the fact the [O II] 3726, 3728 Å doublet would be readily resolved at the spectral resolution of ESI.

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[2]This redshift is presumably a slight overestimate by an unknown amount given the likelihood of self-absorption.
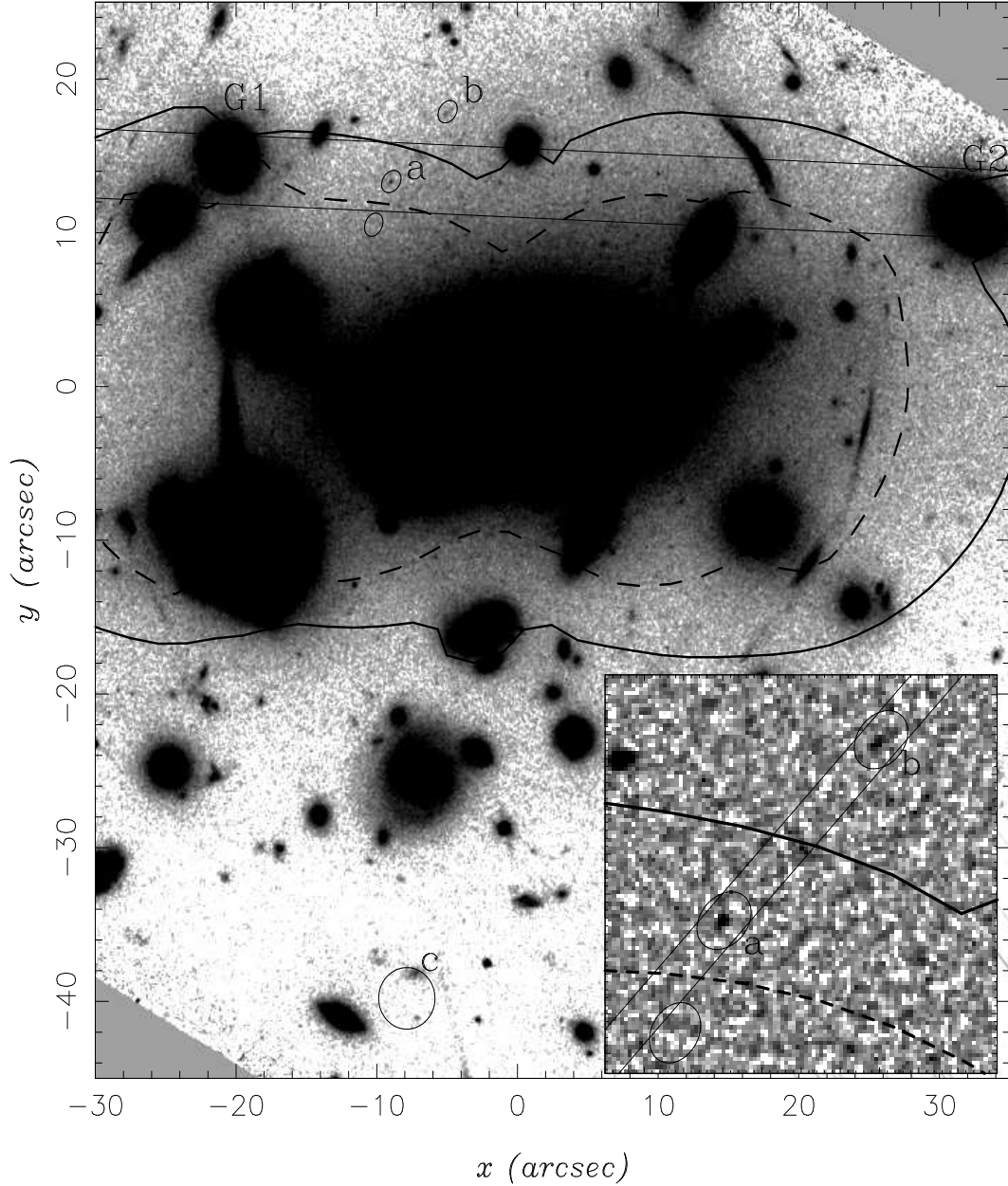
Figure 1: *Hubble Space Telescope F814W image of Abell 2218 (z=0.18) with the location of the LRIS longslit scanning region marked.* a *and* b *represent the lensed pair at z=5.576; the inset panel (10 × 10 arcsec) illustrates the secondary spectroscopic configuration adopted with ESI. Curves refer to critical lines of infinite magnification for a source at z=1.14 (dashed) and 5.576 (solid) in the context of Kneib et al's (1996) mass model. For a source at z=1.14, the counter-image of* a *would lie just below the appropriate critical line (as indicated by the small circle) and is not seen. The large circle* c *refers to the region where a much fainter (I ∼29) third image is expected for a source at z=5.576.*
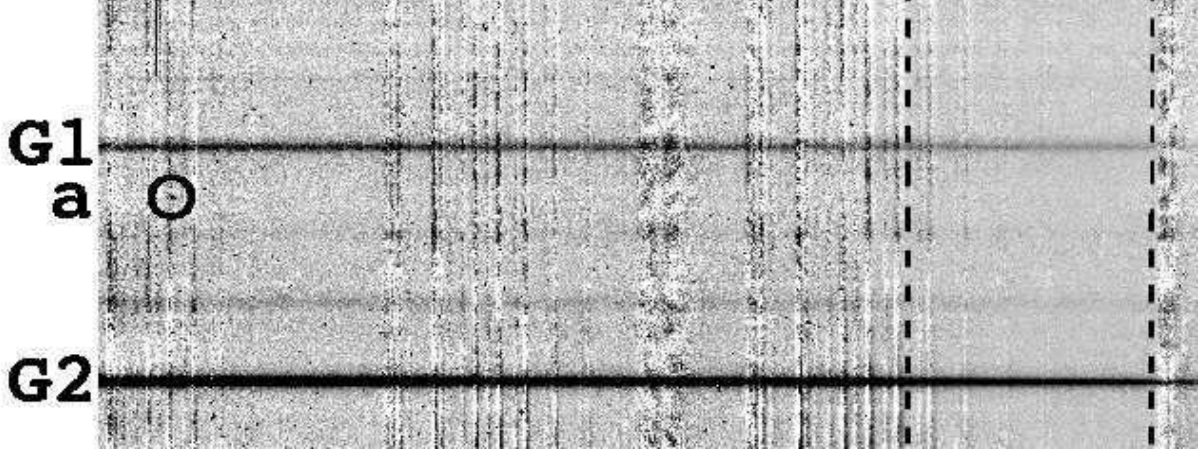
Figure 2: *The discovery of an emission line source close to the cD in the rich cluster Abell 2218. Keck I LRIS-R spectral image of a region 100 arcsec in extent covering $\lambda\lambda 6700$-9350 Å with the emission line attributed to object* a *at $\lambda 7989$ Å marked. The dashed lines at longer 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 *labelled in Figure 1 are marked.*
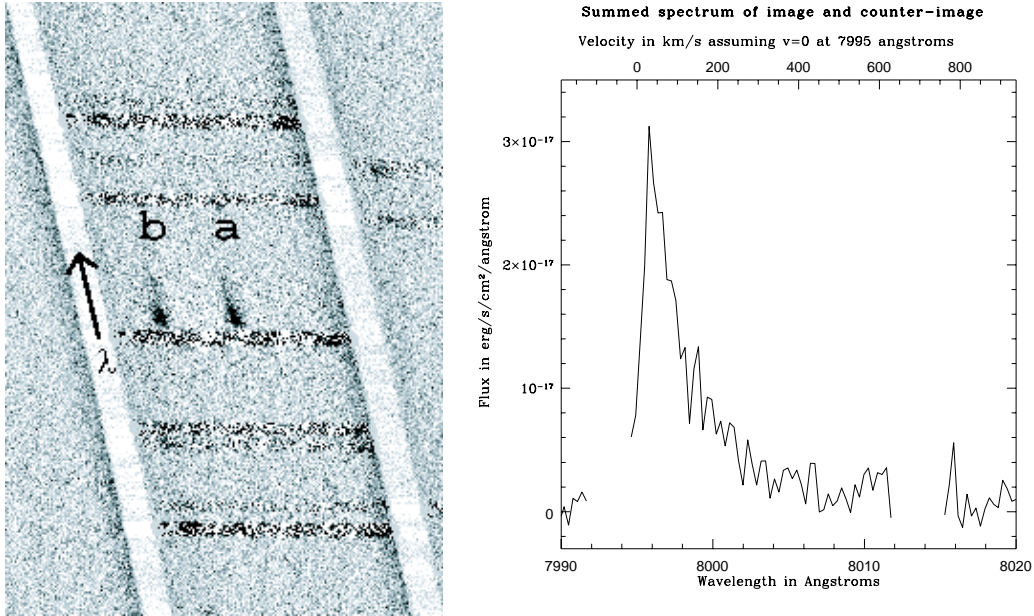
Figure 3: *Confirmation of strong emission in the pair of images marked in Figure 1 using the Keck II Echelle Spectrograph and Imager. (a) 2-D sky subtracted spectral image using the 20 arcsec slit. (b) Flux-calibrated spectrum of the region around Lyman alpha emission combined from both images revealing a P-Cygni like profile extending redward by $\simeq 200$ km sec^{-1} in the rest-frame. The redshift corresponding to the peak emission is z=5.576.*

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 Figure 1b 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 (1999). In this model, the magnifications for a and b are, respectively 3.8 mag ($\times$33.1) and 3.7 mag ($\times$30.2) implying a (unlensed) source magnitude of $I_{814} \simeq 29.7$. Inspection of the dithered WFPC2 image indicates that image a is marginally resolved along the shear direction (i.e. towards the other image). The appropriate half-light scales are 0.23 $\times$ <0.15 arcsec. 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 [3].

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. a HII 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 sub-component of a larger luminous system (c.f. Franx et al 1997, Trager et al 1997).

A substantial component of the broad-band 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 λ7989, the flux density in the line would be $F_a(HST)$=1.2 $\pm$ 0.2 10^{-16} ergs cm^{-2} sec^{-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 10^{-17} ergs cm^{-2} sec^{-1}. The ESI line flux is consistent, within uncertainties of absolute calibration, with that inferred for a in the LRIS data: $F_a(LRIS)$=5.6 $\pm$ 0.5 10^{-17} ergs cm^{-2} sec^{-1}.

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

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[3]We assume a cosmological model with Ω_M=0.3 and Ω_Λ=0.7 througout.

emission line flux.

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

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 narrow band 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 of stars. Although the Lyα line is an unreliable guide to the ongoing star formation rate because of self-absorption, scattering and dust extinction difficulties, will argue that uncertainties arising from this diagnostic most likely strengthen our conclusions.

Adopting the relationship 1 $M_\odot$ yr^{-1} = 1.5 10^{42} ergs sec^{-1} in Lyα (Ferland & Osterbrock 1985, Kennicutt 1998, Osterbrock 1989,) and including a magnification of 33 with a 100% escape fraction and zero extinction, we infer a current star formation rate (SFR) of 0.5 $M_\odot$ yr^{-1}. We consider this a lower limit given the conservative assumptions above. Although our physical scale of <150pc 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 HII region with a luminosity $L_\alpha \simeq 10^{42}$ ergs sec^{-1} (c.f. Melnick et al 2000).

At z=5.576, in our adopted cosmology, the cosmic age is only 1 Gyr. We ran the Starburst99 code (Leitherer et al 1999) for a metal-poor (Z=$10^{-3}Z_\odot$) system with a constant SFR of 0.5 $M_\odot$ yr^{-1} in order to explore at what age a detectable stellar continuum would emerge in the LRIS spectral window ($\lambda_{UV} = \lambda_{rest}$=1370–1415 Å). 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 $F_{UV} < 3.\,10^{-20}$ ergs cm^{-2} Å $^{-1}$ (see §2), the appropriate unlensed continuum luminosity, $L_{UV} < 2.\,10^{39}$ ergs sec^{-1} Å $^{-1}$, 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 Lyα 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 Lyα 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 $z \simeq 6$ (Haiman & Spaans 1999). Our critical line survey (Santos et al 2001) will provide new constraints on their abundance and redshift distribution out to $z \simeq 7$. 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 star formation rate deduced from the Lyα flux. While there are many uncertainties in this deduction, we argue 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 μm, i.e. in the rest-frame optical. Depending on the star formation history, lensed 2μm fluxes of 50 nJy ($K \simeq 25$) are expected. An unlensed analog would have a flux density of only 1 nJy and would clearly be challenging even for NGST.

HII regions of stellar mass of order 10^6 $M_\odot$ with star formation rates of $\simeq 1\,M_\odot$ 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 re-ionization may be occurring (Djorgovski et al 2001, Becker et al 2001). Just as with those constraints which sample a few (possibly atypical) sightlines 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 $z \simeq 5$.

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Table 1.   Unlensed Source Fluxes

Dataset	Total	continuum[a]	Ly-α
	mag	erg cm^{-2} s^{-1} Å^{-1}	erg cm^{-2} s^{-1}
HST/WFPC2 F814W	29.7	$< 2.4\ 10^{-20}$	$< 3.6 \pm 0.6\ 10^{-18}$
LRIS		$< 6\ 10^{-21}$	$1.7 \pm 0.2\ 10^{-18}$
ESI			$2.1 \pm 0.2\ 10^{-18}$
WHT J	> 26.3	$< 8\ 10^{-20}$	
WHT K	> 25.3	$< 2\ 10^{-20}$	

[a]   3-σ upper limits on the continuum flux, per unit wavelength in the rest frame.