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Discovery of a faint *R*-band drop-out: A strongly reddened lensed star forming galaxy at $z = 1.68^{\star}$

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Abstract. We report the discovery of an unusual emission line galaxy at redshift $z = 1.68$ found from near-IR imaging and spectroscopic observations with ISAAC/VLT of a faint gravitationally lensed *R*-band drop-out behind the lensing cluster Abell 1835. From the emission lines of [O III] $\lambda\lambda$4959, 5007, and Hβ this galaxy shows a moderate to high excitation and line equivalent widths typical of relatively metal-poor H II galaxies. Its apparent *J* magnitude translates to an absolute *B*-band magnitude $M_B \sim -16.4$ once corrected for a gravitational magnification of 1.8 mag. This makes it one of the faintest intermediate redshift galaxies known so far.
From the presence of emission lines and the available *VRIJHK* photometry we determine constraints on its dominant stellar population. The only viable fit found is for a fairly young (~6−9 Myr) burst suffering from a considerable extinction ($A_V \sim 1.2{-}1.8$ mag). We find that this object resembles strongly H II galaxies and intermediate redshift compact emission line galaxies, albeit suffering from a larger extinction than usual. We also discuss the possible contamination introduced by such *R*-band drop-out galaxies in searches for $z \gtrsim 5$ galaxies.

Key words. galaxies: high-redshift – galaxies: evolution – galaxies: starburst – galaxies: active – infrared: galaxies

1. Introduction

The strong lensing effect due to clusters of galaxies – typically yielding a magnification by 1–3 mag – has extensively been used in the last decade to identify and to probe the population of galaxies at $z \gtrsim 1$ towards the faint end of the luminosity function and beyond the limits of conventional spectroscopic samples (see e.g. Mehlert et al. 2001; Ellis et al. 2001; Pelló et al. 2003 and references therein).

The development of near-IR spectrographs on 10m class telescopes has allowed the study of the rest-frame optical properties of galaxies using the same emission lines all the way from the local universe to $z \sim 4$ (Pettini et al. 2001; Erb et al. 2003). The contribution of lensing clusters to these detailed studies is already significant. In particular, the metallicity–luminosity and the mass–metallicity relations for intrinsically faint lensed galaxies, as compared to reference samples at different redshifts, have recently been studied by Lemoine-Busserolle et al. (2003). Despite these efforts, the sample of $z \sim 1$–3 galaxies observed spectroscopically in the near-IR is still dramatically small. Furthermore all of these objects were selected from optical imaging and spectroscopy.

Here we report the discovery of a faint emission line galaxy at $z \sim 1.7$ (named #2582 hereafter) discovered recently during near-IR spectroscopic observations targetting $z \sim 8$ to 10 candidates selected from deep *JHK* ISAAC imaging in a $2' \times 2'$ field centered on the lensing cluster Abell 1835 that reached depths of 25.1 in *J*, 24.3 in *H* and 24.3 in *K* (3σ on 4 pixels, Vega system). This survey area corresponds to about 2.9 arcmin^2 at $z = 1.7$, after correction of lensing magnification. Object #2582 fulfills the following photometric selection criteria: it is an *R*-band drop-out on HST images, with blue $H - K \leq 0.5$ and red $J - H \geq 0.8$. Because this object was marginally detected in *I*, it was considered as an interesting secondary target, potentially a $z \gtrsim 5$ galaxy or possibly a source of "contamination" in searches for high *z* galaxies. Results on this specific project will be reported elsewhere (Richard et al., in preparation). Furthermore, with $R - K \gtrsim 4$ this object is quite red, although not exactly comparable to extremely red objects (ERO). Our observations thus reveal that we are dealing with a previously unknown type of galaxy at intermediate redshift: a strongly reddened low-luminosity star-forming galaxy.

In Sect. 2 we summarize the observations used in the present study. The spectroscopic properties of #2582 and its

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* Based on observations collected with the ESO VLT-UT1 Antu Telescope (70.A-0355, 271.A-5013), the Hubble Space Telescope (*HST*) and the Canada-France-Hawaii telescope.

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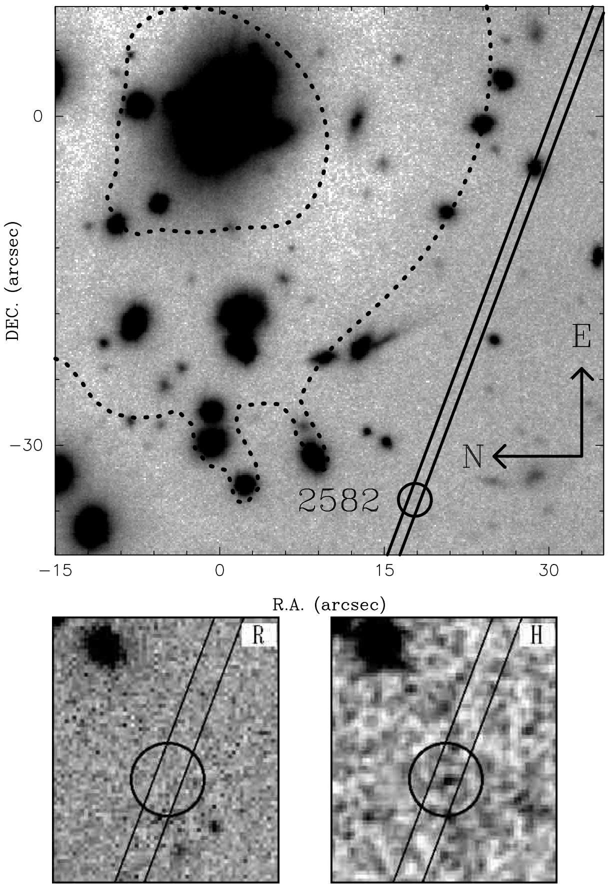

Fig. 1. Composite *JHK*s ISAAC image of the cluster Abell 1835 (top), showing the location of object #2582 (circle) and the slit configuration used for spectroscopy with ISAAC. Superposed are the theoretical critical lines at $z = 1.6755$. On the bottom, close-ups images in the *R*-band (F702W) *HST*/*WFPC2* (left) and the *H*-band ISAAC, smoothed with a sigma = 1 pixel Gaussian (right).

nature are addressed in Sects. 3 and 4 respectively. Implications from our finding are discussed in Sect. 5.

2. Photometric and spectroscopic data

Ultradeep *JHK*s images were obtained with ISAAC/VLT on the central 2×2 arcmin of Abell 1835 ($z = 0.253$), with ISAAC/VLT in service mode during February 2003. Photometric data were complemented by deep *VRI* observations taken at CFHT, and WFPC2/HST images in the *R* band (F702W, Smith et al. 2003). Photometry was performed using the *SExtractor* package (Bertin & Arnouts 1996). A full report of these observations, including particular data reduction procedures, will be published elsewhere.

During a run between 29 June and 3 July 2003 we have carried out spectroscopic observations in the *J* band with ISAAC (SW mode) which included #2582 as a secondary target aligned "coincidentally" in the slit position shown in Fig. 1. The slit width was 1″, and the seeing varied between 0.4″ and 0.5″. The coordinates of this object are $\alpha_{2000} = 14{:}01{:}00.700$, $\delta_{2000} = +02{:}52{:}09.55$.

Spectra were obtained in beam-switching mode between two positions A and B, following a sequence ABBA (see e.g. Cuby et al. 2003[1]; Lemoine-Busserolle et al. 2003) Spectroscopic data where reduced using IRAF procedures and conforming to the ISAAC Data Reduction Guide 1.5[2]. The first sky-subtraction was performed by subtracting one frame from the other in each AB pair. After removing the 50 Hz pickup that occured during the last night and flat-fielding these frames, we wavelength-calibrated the two-dimensional spectra using the atlas of OH lines (Rousselot et al. 2000). Finally, we combined each A−B and B−A frames after suitable shifts and extracted the one-dimensional spectrum. We used the observed telluric standards to flux-calibrate and correct for telluric features in the individual spectra, fitting the hot (O and B) stars with a blackbody curve.

Table 1. Main properties of images (central wavelength, exposure time, seeing and pixel size) and photometry of target #2582 in the Vega and AB systems, obtained within 1.5″ aperture on seeing matched images. Error bars are from SExtractor. Limiting magnitudes correspond to a detection limit of 3σ on 4 pixels.

Filter	$\lambda_{\rm eff}$ [μm]	$t_{\rm exp}$ [ksec]	σ [″]	pix [″]	mag [Vega]	mag [AB]
V (1)	0.54	3.75	0.76	0.206	>28.3	>28.3
R (1)	0.66	5.4	0.69	0.206	>28.3	>28.5
I (1)	0.81	4.5	0.78	0.206	26.8 ± 0.47	27.3
J (2)	1.26	6.48	0.65	0.148	24.7 ± 0.45	25.6
H (2)	1.65	13.86	0.50	0.148	23.7 ± 0.16	25.1
*K*s (2)	2.16	18.99	0.38	0.148	24.3 ± 0.30	26.2

(1) Czoske et al. (2002); (2) Richard et al., in preparation.

3. Results

Table 1 summarizes the photometric data obtained on object #2582, computed within a 1.5″ aperture on seeing matched images. This source is unresolved, and it is not detected on the WFPC2/HST image ($\mu_{F702W} \geq 23.8$ mag/arcsec^2 and $R_{F702W} \geq 27.3$, 2σ on 4 HST pixels). It is undetected in *V* and *R* and only marginally detected in *I*. This object would never have been selected from our optical data, since it is only marginally detected in the *I* band.

The spectroscopic observations revealed the presence of 3 emission lines in 2 overlapping regions of the *J* band: 1.285−1.345 μm and 1.335−1.395 μm, observed with exposure times of 10.8 and 18.9 ksec respectively. These lines were identified as [O III] $\lambda\lambda$4959, 5007 and Hβ at wavelengths corresponding to an average redshift of $z = 1.676$ for this IR-selected source. The corresponding 2D and extracted spectra are shown in Fig. 2. As seen on the 2D spectrum, the "trace" of the spectrum does not follow a detector line. Extraction (with iraf task apall) was done by shifting the fitted "trace" of the spectrum of the brighter star used for slit alignement onto the position of the [OIII]5007 Å line of #2582. The observed line

[1] ISAAC User Manual: `http://www.eso.org/instruments/isaac/ userman/umhtml1121/index.html`

[2] `http://www.hq.eso.org/instruments/isaac/index.html`

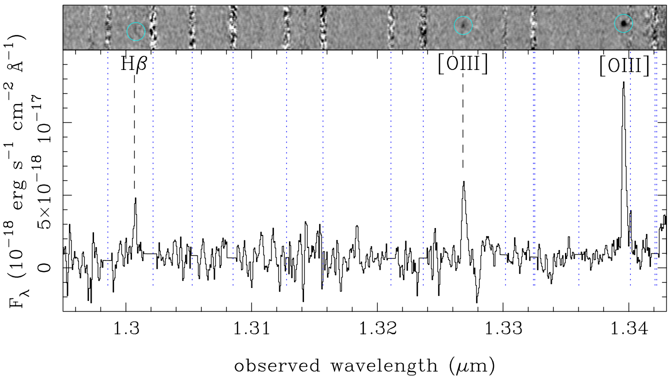

Fig. 2. 2D and extracted spectra of #2582 showing the wavelength interval between [O III] 5007 and Hβ. The extracted spectrum is flux calibrated and corrected for distorsion. Dotted vertical lines display the position of the main OH lines.

Table 2. Emission lines detected in the target #2582, uncorrected for lensing magnification.

Line Id.	z	F_λ 10^{-17} erg/s/cm^2
[O III] λ5007	1.6755	3.93 ± 0.1
[O III] λ4959	1.6757	1.39 ± 0.1
Hβ	1.6759	0.66 ± 0.1

fluxes are given in Table 2. Because of the excellent seeing conditions and the slit width, we can safely consider that the bulk of the flux from this unresolved source was included in the slit. The lines are not resolved as compared to the instrumental profile measured using the OH sky lines. Thus, the line-of-sight velocity dispersion σ should be smaller than 20–30 km s^{-1}.

From simple SED fit (cf. below) and adopting "concordance" cosmological parameters[3], the apparent J magnitude translates to an absolute B-band magnitude $M_B \sim -18.2$. Corrected for the magnification factor of 1.8 mag obtained from the lensing model by Smith et al. (2002), this yields an absolute magnitude of only $M_B \sim -16.4$. Even taking the apparently high extinction into account (cf. below) this still corresponds to $M_B \sim -18.$ to -18.8. To the best of our knowledge, this makes it the faintest starforming source at intermediate redshift for which spectroscopic data have been obtained. We now discuss the possible nature of this faint galaxy.

4. The nature of the $z = 1.676$ galaxy #2582

The observed line ratio [O III] λ5007/H$\beta \sim 5.9$ is of moderate to high excitation typical of relatively metal-poor H II galaxies whose emission lines are predominantly powered by star formation. The emission lines are unresolved, and thus we can exclude a Seyfert 1 galaxy, but in principle not a Seyfert 2. However, the #2582 object is fainter than most Sey 2 (cf. Ho et al. 1997) even if corrected for extinction. With an absolute magnitude of $M_B \sim -16.4$ (or ~ -18 to -18.8 after extinction

[3] $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}.

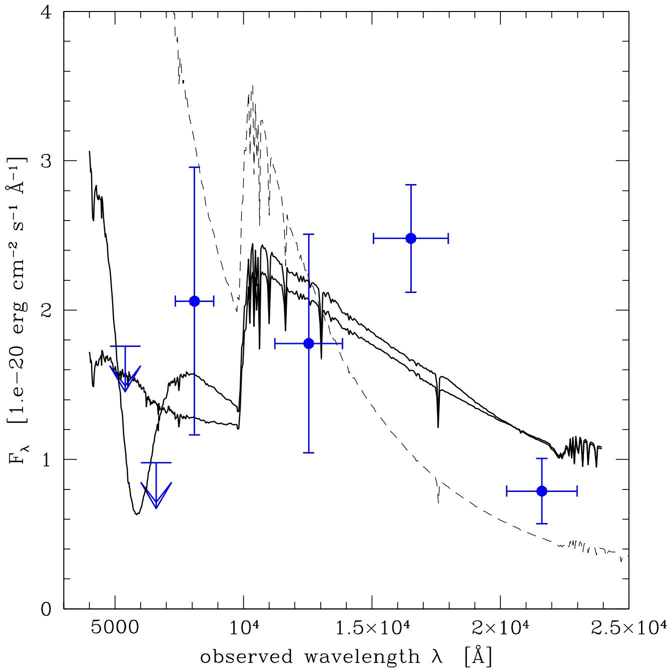

Fig. 3. Observed and modeled broadband SED of #2582 covering the *VRIJHK* bands. The J and H-band fluxes have been corrected for line emission as indicated in the text. Error bars correspond to 1σ. The two best fit spectra using the Seaton (1979) Milky Way extinction law and the Calzetti et al. (2000) attenuation law for starbursts are shown by solid lines. The corresponding extinction is $A_V \sim 1.2$ to 1.8 mag respectively. The unreddened model SED of a 6 Myr old burst (taken here for a metallicity of 1/2.5 solar) is shown by the dashed line.

correction) this galaxy is fainter than Lyman break galaxies at $z \sim 3$ by at least 3 mag, but similar to the compact narrow emission line galaxies (CNELG) at $z < 1.4$ of Guzman et al. (1997). The Hβ luminosity (L(Hβ) $\sim 1.2 \times 10^{41}$ erg s^{-1}) is also comparable to that of CNELG, and to the bright end of H II galaxies in the local Universe.

The observed emission lines contribute to ~56% of the observed J-band flux within the slit. Assuming Case B recombination and zero ($A_V \sim 1.8$ mag) extinction a lower limit to the contribution of Hα to the H-band is estimated to ~17 (30)%. We do not expect significant contamination from other emission lines on the remaining filters. After correction of the observed broad band flux for the emission lines, the following estimate is obtained for the rest-frame Hβ equivalent width: $W(\mathrm{H}\beta)_{\mathrm{rest}} \sim 139$ Å. Whereas smaller equivalent widths are typically observed in large starburst galaxies and in some CNELG, such values are fairly common in low metallicity H II galaxies (e.g. Stasińka & Izotov 2003).

The broad-band SED plotted in Fig. 3 provides further information on the properties of this object. Basically such a SED can only be reconciled with a population showing a strong Balmer break and little extinction or a younger stellar population strongly extinguished in the rest-frame UV. This is quantitatively confirmed by SED fits of numerous templates using the code of Bolzonella et al. (2000), including spectra from the 2001 version of Bruzual & Charlot (1993) models, Starburst99 (Leitherer et al. 1999), and observed galaxy templates from Coleman et al. (1980) and Kinney et al. (1996). The best fits correspond to burst models with ages ~360−510 Myr and little or no extinction, or bursts of ages ~6−9 Myr with $A_V \sim 1.2$–1.8 mag depending on the adopted extinction law. The former explanation is excluded as populations of such age are not compatible with the presence of emission lines indicative of young (≲10 Myr) massive stars. Furthermore, if present (in quantities sufficient to explain e.g. the observed Hβ flux) the young population will dominate the rest-frame UV–optical spectrum. We therefore conclude that the only consistent explanation for the observed SED of #2582 is that it is dominated by a young (~6−9 Myr) population which suffers from a strong extinction.

This best fit reproduces the observed SED to within ~1–2 σ, as shown in Fig. 3, using two different extinction laws: Calzetti et al. (2000) for starbursts, with $A_V \sim 1.6$–1.8 mag, and the Seaton (1979) Milky Way extinction law with $A_V \sim 1.2$–1.4 mag. The later produces a strong "absorption bump" at ~5900 Å. Thus, we are probably dealing with a low-metallicity and dusty young starburst.

The best consistency checks of our explanation on the nature of this source will probably be through Hα spectroscopy, in order to confirm the large extinction and to exclude the Sey 2 possibility. Deeper optical imaging, including the Z-band, will improve the constraints on the overall SED. Measurements of other emission lines such as [O II] λ3727, [NII]$\lambda\lambda$6548, 6584, and [S II] $\lambda\lambda$6717, 6731 will also provide a better understanding of the physical properties and of the nature of this source.

5. Discussion and conclusions

The V and R-band drop-out technique has recently been applied by various authors in searches of $z \gtrsim 5$ galaxies. E.g. Lehnert & Bremer (2003) use RIz images taken with the VLT and apply a $R_{AB} - I_{AB} \geq 1.5$ color criterion to select galaxies with $z > 4.8$. Iwata et al. (2003) adopt the $V - I_c \geq 2.0$ "drop-out" and a combined $V - I_c$ and $I_c - z'$ criterion to determine luminosity functions and star formation rates of $z > 5$ galaxies from their SUBARU data. Would the #2582 object, a V and R-band drop-out, be selected as a high-z candidate?

The galaxy #2582 has $R_{AB} - I_{AB} > 1.2$ and $V - I > 1.5$, close to the above selection criteria but not formally above the generally adopted bounds. If deeper optical imaging was available in V or R and I, #2582 might have been detected in these bands. Furthermore, the red $R-K$ color makes it a lower priority candidate for $z > 5$ objects selection. However, because of the large equivalent width of its lines, this class of objects is a problem for searches based on narrow-band only such as Rhoads et al. (2003) and for future $z \geq 7$ searches with narrow band filters in the J band. In order to unambiguously detect $z > 5$ sources, a combination of photometry and spectroscopy, similar to the approach of Lehnert & Bremer (2003) or our own, is probably to be preferred.

From our observations we conclude that young strongly reddened starbursts are potential contaminants of high-z galaxy samples together with stars and low-z elliptical galaxies. However, from the existing data it is too early to estimate the fraction of such "contaminants" to photometric samples of $z \gtrsim 5$ candidates.

Finally we may speculate that the classical criteria used to search for intermediate redshift galaxies probably miss objects like the one found here quite independently of the lensing magnification also employed here. The true number of intermediate z emission line galaxies observable with near-IR spectrographs is probably larger than presently thought.

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