Stellar populations and Lyα emission in two lensed $z \gtrsim 6$ galaxies

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ABSTRACT

We present an analysis of two strongly lensed galaxies at $z = 6.56$ and $z \sim 7$ for which multi-band photometric and spectroscopic observations are available. For one source the data include recent HST and Spitzer observations. Using an SED fitting technique considering a number of parameters (various libraries of empirical and theoretical template spectra, variable extinction and extinction laws) we attempt to constrain the properties of their stellar populations (age, star formation history, mass) and their intrinsic Lyα emission. The following main results are obtained for the individual galaxies:

• **Triple arc in Abell 2218, probable $z \sim 7$ galaxy:** The most likely redshift of this source is $z \sim 6.0–7.2$ taking into account both our photometric determination and lensing considerations. SED fits indicate generally a low extinction ($E(B-V) \lesssim 0.05$) but do not strongly constrain the star formation (SF) history. Best fits have typical ages of $\sim 3$ to 400 Myr. A reasonable maximum age of (250–650) Myr (1 $\sigma$ interval) can be estimated. However, the apparent 4000 Å break observed recently from combination of IRAC/Spitzer and HST observations, can also equally well be reproduced with the template of a young ($\sim 3–5$ Myr) burst where strong restframe optical emission lines enhance the 3.6 and 4.5 µm fluxes. The estimated SFR is typically $\sim 1$ M$_\odot$ yr$^{-1}$ for a Salpeter IMF from 1-100 M$_\odot$, in agreement with previous estimates. The knowns on the age and star formation history could easily explain the apparent absence of Lyα in this galaxy.

• **Abell 370 HCM 6A:** The available Lyα and continuum observations indicate basically two possible solutions: 1) a young burst or ongoing constant SF with non-negligible extinction or 2) a composite young + “old” stellar population. In the first case one obtains a best fit $E(B-V) \sim 0.25$, or $A_V \sim 0.5–1.8$ at a 1 $\sigma$ level. In consequence we obtain SFR $\sim 11–41$ M$_\odot$ yr$^{-1}$ for a Salpeter IMF from 1-100 M$_\odot$, in agreement with previous estimates. Other properties (age, SF history) remain largely unconstrained. In case of composite stellar populations the SFR, mass, and luminosity estimate is lower. The two scenarios may be distinguishable with IRAC/Spitzer observations at 3.6 and 4.5 µm.

Key words: Galaxies: high-redshift – Galaxies: evolution – Galaxies: starburst – Cosmology: early Universe – Infrared: galaxies

1 INTRODUCTION

Little is known about the stellar properties, extinction, and the expected intrinsic Lyα emission of distant, high redshift galaxies. Indeed, although it has in the recent past become possible through various techniques to detect already sizeable numbers of galaxies at $z \gtrsim 5$ (see e.g. the reviews of Taniguchi et al. 2003 and Spinrad 2004) the information available on these objects remains generally scant. For example, in many cases the galaxies are just detected in two photometric bands and Lyα line emission, when present, serves to determine the spectroscopic redshift (e.g. Bremer et al. 2004, Dickinson et al. 2004, Bunker et al. 2004). Then the photometry is basically used to estimate the star forma-
tion rate (SFR) assuming standard conversion factors between the UV rest-frame light and the SFR, and nothing is known about the extinction, and the properties of the stellar population (such as age, detailed star formation histories etc.)

At higher redshift (\(z \gtrsim 6\)) even less information is generally available (but see a recent study of Eyles et al. 2005 on two \( z \sim 6\) galaxies observed with HST and Spitzer). Many objects are found by Ly\(\alpha\) emission, but remain weak or sometimes even undetected in the continuum (e.g. Rhoads & Malhotra 2001, Kodaira et al. 2003, Cuby et al. 2003, Ajiki et al. 2003, Taniguchi et al. 2004). In these cases the Ly\(\alpha\) luminosity can be determined and used to estimate a SFR using again standard conversion factors. Also the Ly\(\alpha\) equivalent width is estimated, providing some possible clue on the nature of these sources. However, this has lead to puzzling results e.g. for the sources from the LALA survey which seem to show unusually large Ly\(\alpha\) equivalent widths that are difficult to understand without invoking exceptional conditions (PopIII stars?; Malhotra & Rhoads 2002, Rhoads et al. 2003). Given the few data available for the LALA sources it is fair to say that the nature of these objects, their stellar populations, extinction etc. remain currently largely unknown (cf. Dawson et al. 2004). When possible, a simple comparison between the UV and Ly\(\alpha\) SFR is undertaken providing possibly information on the Ly\(\alpha\) transmission, i.e. the partial absorption of Ly\(\alpha\) photons on their sight line through the intergalactic medium (e.g. Haiman 2002, Santos 2004) and/or on partial Ly\(\alpha\) “destruction” processes close to the source (e.g. due to dust or ISM geometry; Charlot & Fall 1993, Valls-Gabaud 1993, Tenorio-Tagle et al. 1999, Mas-Hesse et al. 2003).

Notable exceptions of \(z \gtrsim 4\) samples for which some estimate of extinction is available from multi-band photometry include work on the Subaru Deep Survey (Ouchi et al. 2004) and GOODS data (e.g. Papovich et al. 2004). Lehnert & Bremer (2004) also discuss some preliminary information on little extinction in their \( z > 5 \) sources. Interestingly, in their study of a \( z = 5.34 \) galaxy discovered by Dey et al. (1998), Armus et al. (1998) find indications for significant reddening (\(A_V > 0.5\) mag) from analysis of the observed SED and from the presence of Ly\(\alpha\) emission.

In a similar manner we will here present a consistent study of the stellar population properties, extinction, and Ly\(\alpha\) emission for two galaxies at redshift \( z \gtrsim 6\). For this aim we use two distant (\(z \gtrsim 6\)) gravitationally lensed galaxies for which multi-band photometry is available (detection in at least 3–4 bands). Through a quantitative analysis of their SED, using a vast library of empirical and theoretical template spectra, we aim to constrain properties of the stellar populations, such as age and star formation (hereafter SF) history (burst or constant SF?) and their extinction. Furthermore by comparing the Ly\(\alpha\) emission expected from the stellar population constraint with the observed Ly\(\alpha\) flux we estimate consistently the Ly\(\alpha\) “transmission” for the individual sources.

The Ly\(\alpha\) transmission and SF properties derived here can in principle be used to infer the ionisation fraction of hydrogen in the IGM at a given redshift (cf. Haiman 2002, Santos 2004), a key quantity of interest for the study of the reionisation history of the Universe (cf. review from Barkana & Loeb 2001). Obviously the present “exploratory” work will have to be extended to larger galaxy samples, and sophisticated tools will probably be needed to interpret such results in terms of IGM properties (cf. Gnedin & Prada 2004). However, this approach should be complementary to other methods probing the reionisation history by measuring the Gunn-Peterson optical depth observed in quasar spectra as a function of redshift (e.g. Becker et al. 2001, Fan et al. 2003), or by comparing Ly\(\alpha\) luminosity functions at different redshifts (e.g. Malhotra & Rhoads 2004).

The remainder of the paper is structured as follows. In Sect. 2 we summarise the adopted observational constraints from the literature. Our modeling technique is described in Sect. 3. The detailed results for each galaxy are presented in Sects. 4 and 5. Our main conclusion are summarised in Sect. 6.

### 2 OBSERVATIONAL CONSTRAINTS

The two galaxies studied here are: 1) The probable \( z \sim 7\) galaxy recently discovered by Kneib et al. (2004, hereafter KESR), which presently lacks of a spectroscopic redshift but for which rather accurate multi-band HST observations are available, allowing us in particular also to derive a fairly reliable photometric redshift. 2) the \( z = 6.56 \) Ly\(\alpha\) emitter HCM 6A behind the lensing cluster Abell 370. We now summarise the observational data, taken from the literature. The adopted redshift and gravitational magnification factors are listed in Table 1.

Before proceeding let us mention for clarity that these two objects are generally considered to be star forming galaxies (starbursts), not AGN (narrow line - type II - or others), as no contradicting information is available so far. However, one must bear in mind that some of the interpretations presented below (and in the literature) may need to be revised, should this assumption be incorrect.

**Triple arc in Abell 2218**: The observational data for this object, named Abell 2218 KESR hereafter, is taken from Kneib et al. (2004, hereafter KESR) and from Egami et al. (2005). The photometry from KESR includes observations with HST (WFPC2, ACS, NICMOS) in V\(_{606W}\) (undetected), I\(_{814W}\), z\(_{850LP}\), and H\(_{160W}\), and with NIRC/Keck in J. Subsequently, additional photometry was obtained with NICMOS/HST in the J band (F110W), and with IRAC/Spitzer at 3.6 and 4.5 \(\mu m\) (see Egami et al.) For our computations (see below) we have used the appropriate filter transmission curves. In particular, updated transmission curves were used for the ACS and NICMOS filters (M. Sirianni 2003, private communication; Sirianni et al. 2004; R. Thompson 2003, private communication).

Few brief comments concerning the photometry are needed here. First, KESR present photometry for two multiple images (a and b). Apparently sources a and b differ in the z\(_{850LP}\) flux (with quoted errors of \( \pm 0.05\) mag) by 3.2 \(\sigma\), whereas the fluxes in the other filters agree well within 1 \(\sigma\). Differential lensing across the images together with sampling effects could be responsible for this small discrepancy. As we are interested in a global representative SED for this source, we have chosen to use the averaged photometric SED, the magnification factors being the same for the two images. Finally, we have also noted some apparent discrepancies between the measurements reported in KESR and Egami et
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al., the most important one being the H\(160\mu\text{m}\) flux, which is \(~15-20\%\) \((3-4\sigma)\) higher in the latter publication. These differences are mostly due to the use of different apertures on different repixeled/rescaled images \(\text{(J. Richard, 2004, private communication)}\). Again, this illustrates the difficulty in deriving reliable colors for extended arcs. To account for these small discrepancies and for the possible error underestimate we therefore adopt a minimum photometric error of 0.15 mag in all filters. It is worth noting that photometric errors translate into absolute flux calibration errors for fitting purposes. As we will see below, adopting the latter minimum errorbars significantly improves the SED fits.

In addition to the photometry, the non-detection of the source with Keck LRIS spectroscopy provides an upper limit on the continuum flux between 9000 and 9300 \AA\ (KESR). This upper limit will be used as an additional constraint in our SED modeling. KESR also indicate a possible drop of the continuum below \(~9800\) \AA\ from their Keck II NIRSPEC spectrum. For various reasons the reality of this spectral break is questionable. First a true neutral hydrogen break \("\Lya break\") at \(~9800\) \AA, far in the red wing of the \(z_{850\mu\text{m}}\) filter, seems incompatible with the relatively strong flux measured in this filter. Furthermore, test computations show that such a break is difficult if not impossible to reconcile with our spectral modeling. In any case the significance of this finding appears questionable as the detected continuum is extremely faint and noisy. The reality of this spectral feature is also questioned by Egami et al. (2005). For these reasons this information is discarded from our spectral fitting.

In practice we have retained the following two variants to describe the observed SED of this source: \textit{SED1}) The average fluxes \((I_{110\mu\text{m}}, z_{850\mu\text{m}}, H_{160\mu\text{m}}, H_{110\mu\text{m}})\) of images \(a\) and \(b\) from KESR plus the IRAC/Spitzer data of image \(b\) from Egami et al. \textit{SED2}) All fluxes from image \(b\) from Egami et al. These are treated as SEDs from two different objects. Furthermore, for each of these \("objects\) we have computed two cases in our SED fitting described below: \(i)\) The observed SEDs in \(I_{110\mu\text{m}}, z_{850\mu\text{m}}, H_{110\mu\text{m}}, H_{160\mu\text{m}}, 3.6, \text{and} 4.5\ \mu\text{m}. \(ii)\) Same as \((i)\) plus the flux limits from the \(V_{606\mu\text{m}}\) and Keck LRIS non-detections.

No emission line has so far been detected for Abell 2218 KESR. Its spectroscopic redshift remains therefore presently unknown but the well-constrained mass model for the cluster strongly suggests a redshift \(z \gtrsim 6\) for this source \(\text{(KESR, Egami et al. 2005)}\). The magnification factors of both images \(a\) and \(b\) is \(\mu = 25 \pm 3\), according to KESR.

\textbf{Abell 370 HCM6A}: The observational data of this \(z = 6.56\) galaxy is taken from Hu et al. (2002). The photometry includes \textit{VRIIZJK}\footnote{From Keck I and II \text{(LRIS and Echellette Spectrograph and Imager)} and from Subaru \text{(CISCO/OHS)}; The gravitational magnification of the source is \(\mu = 4.5\) according to Hu et al. (2002).} and \textit{H\(i\)} from synthesis models of different metallicities and for instantaneous bursts \(\text{(solid lines)}\) and constant SF \(\text{(long dashed lines)}\). Black lines show solar metallicity models, red lines metallicities between \(Z = 10^{-5}\) and zero \(\text{(PopIII)}\), blue lines intermediate cases of \(Z = 0.004\) and 0.0004. The dotted lines show \(\gamma\) if nebular continuous emission is neglected, i.e. assuming pure stellar emission. Note especially the strong degeneracies of \(\gamma\) in age and metallicity for bursts, the insensitivity of \(\gamma\) on \(Z\) for constant SF, and the rather red slope for young very metal-poor bursts. Further discussions in the text is known for this source and since we adjust the observed flux \(\text{(not magnitude)}\) in this band, this should not affect our conclusions.

3 SED MODELING

3.1 Main restframe UV-optical SED features of high-z galaxies and their \textit{information content}.

Before proceeding to the fits of the individual SEDs a brief comment on the available SED features seems appropriate.

For obvious reasons the available SED \(\text{(basically from broad-band photometry)}\) of high-z \((z \gtrsim 6)\) galaxies is primarily limited to the rest-frame UV \(\text{(when observed from the ground)}\) or optical spectrum \(\text{(when available e.g. with Spitzer and future satellite missions)}\). The main information \"encoded\" in this SED is therefore: \(i)\) the neutral HI break \(\text{shortward of } \Lya (\text{hereafter the \"Ly}^\alpha\text{\) break due to the strong or complete Gunn-Peterson trough, 2)\) the slope of the UV spectrum, and 3)\) possibly a 4000 \AA\ break \(\text{(hereafter denoted Balmer break)}\), if present and covered by the observations. In addition the presence of the Ly\(\alpha\) line, mostly used to determine spectroscopically the redshift, provides clear evidence for ongoing massive star formation \(\text{(hereafter SF)}\).

The position of the Ly\(\alpha\) break depends essentially on
redshift. The UV slope depends on the intrinsic spectrum – in turn depending mostly on age and SF history – and on the extinction, i.e. the extinction law and the amount of reddening. The Balmer break becomes visible (in absorption) in the continuum of stellar populations after \( z \gtrsim 10\)–30 Myr. Ly\( \alpha \) emission, if due to stellar photoionisation and not AGN activity, indicates the presence of young (\( z \lesssim 10 \) Myr) massive ionizing stars.

Concerning the UV slope, it is useful to recall that this quantity \(^1\) does not lend itself to determine the metallicity of a star forming galaxy from a theoretical point of view and in terms of individual objects. The reasons are that intrinsically the UV slope shows only small variations with metallicity, and that the slope depends strongly on the exact SF history (see e.g. Leitherer & Heckman 1995, Meurer et al. 1995). This is illustrated in Fig. 1 where the extinction, i.e. the extinction law and the reddening law, and various metallicities between solar and zero (PopII I) are shown.

For the spectral fitting we use a slightly adapted version of the photometric redshift code Hyperz of Bolzonella et al. (2000). Hyperz does standard SED fitting using a number of modeling parameters. The free parameters for the SED modeling are:

1. the spectral template,
2. extinction and the reddening law,
3. a parameter \( f_{\text{red}} \) describing possible deviations from the average Lyman forest attenuation from Madau (1995).

For Abell 2218 KESR the source redshift is also a free parameter.

For the spectral templates we use a large compilation of empirical and theoretical SED, including starbursts, QSO, and galaxies of all Hubble types, and covering various star formation histories (bursts, exponentially decreasing, constant SF) and various metallicities. For most applications we group the templates in the following way:

- **Starbursts and QSOs (hereafter SB+QSO):** this group includes the starburst templates with \( E(B-V) \) from 0.1 to 0.7 from the Calzetti et al. (1994) and Kinney et al. (1996) atlas, the HST QSO template of Zheng et al. (1997), as well as UV-optical spectrum of the metal-poor galaxy SBS 0335-052 with numerous strong optical emission lines (and an extinction of \( E(B-V) \approx 0.09 \), Izotov & Thuan 1998) kindly communicated to us by Yuri Izotov (2002, private communication)

- **BCCWW+:** Bruzual & Charlot (1998, private communication; cf. Bruzual & Charlot 1993) evolving synthesis models assuming bursts, constant star formation, and exponentially decaying star formation histories reproducing present day spectra of galaxies of various types (E, S0, Sa, Sb, Sc, Sd, and Im) plus the empirical E, Sbc, Scd, and Im templates from Coleman et al. (1980), as included in the public Hyperz version.

- **S03+:** Theoretical templates of starburst galaxies from Schaerer (2003) covering metallicities of \( Z = 0.02 \) (solar), 0.008, 0.004, 0.001, 1/50 \( Z_{\odot} \), \( Z = 10^{-5}, 10^{-7} \), and zero metallicity (PopIII). For low metallicities (\( Z \lesssim 10^{-5} \)) these templates have been computed for 3 different assumptions on the IMF. The spectral library includes burst models and models with a constant star formation rate (SFR). For more details see Schaerer (2003). For the present work these computations were extended to cover ages of up to 1 Gyr. These SEDs are available on request from the first author and on the Web\(^2\).

The standard extinction law adopted here is the one from Calzetti et al. (2000) determined empirically from nearby starbursts. We also explore the possible implications of other laws, such as the Galactic law of Seaton (1979) including the 2200 \( \AA \) bump, and the SMC law from Prévot et al. (1984) and Bouchet et al. (1985) showing no UV bump.

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\(^1\) Various definitions of the UV slope exist. The most commonly used ones, generally denoted \( \beta \), are defined as the power-law index of the SED in \( F_\lambda \) versus \( \lambda \) over a certain wavelength interval.

\(^2\) [http://obswww.unige.ch/sfr]
but a steeper increase of the extinction in the UV compared to Calzetti et al.

For the Lyman forest attenuation, Hyperz follows Madau (1995). However, we allow for possible deviations from the mean attenuation by varying the Lyman forest optical depths \( \tau_{\alpha,\beta} \) by a multiplicative factor taking the values of \((f_{\text{Lyf}}, 1, \text{and } 1/f_{\text{Lyf}})\). Typically we adopted \( f_{\text{Lyf}} = 2 \) or 3. Here \( \tau_{\alpha,\beta} \) stands for the optical depths corresponding to the absorption between Ly\( \alpha \) and Ly\( \beta \), and between Ly\( \beta \) and the Lyman limit respectively.

The following other minor changes have been made in our version (1.3ds) of Hyperz. The calculation of the synthetic photometry deals correctly with templates including strong spectral lines (emission or absorption). Furthermore we make sure to use the proper filter transmission curves usually given in photon units. Earlier versions of Hyperz and other codes (e.g. evolutionary synthesis codes) assume sometimes (for “historical” reasons) that transmission curves be given in flux units. In case of wide filters, e.g. such as some ACS/HST filters, this may lead to small differences. Other modifications concern essentially features related to the user interface (additional outputs etc.).

For given choices of the above parameters, the Hyperz code performs a standard minimisation fit to the observed SEDs and determines, for each point in the parameter space, the corresponding \( \chi^2 \) value. Using these \( \chi^2 \) values, it is possible to quantify the probabilities for the main free parameters, namely extinction, age of the spectral template, SF history, etc. When the SED fitting is based on theoretical templates, the SFR value is easily obtained and allows us to compare the expected values for the Ly\( \alpha \) flux to the actual ones.

To convert the observed/adjusted quantities to absolute values we adopt the following cosmological parameters: \( \Omega_m = 0.3 \), \( \Omega_{\Lambda} = 0.7 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

## 4 RESULTS FOR ABELL 2218 KESR

### 4.1 Photometric redshift estimate

As a spectroscopic redshift has not been obtained (yet) for this galaxy we here examine its photometric redshift estimate. In Fig. 2 we show the photometric redshift probability distributions \( P(z) \) for the two SEDs (SED1, SED2) of Abell 2218 KESR described above using the three spectral template groups and adopting a minimum photometric error of 0.15 mag. For each redshift, \( P(z) \) quantifies the quality of the best fit model obtained varying all other parameters (i.e. extinction, \( f_{\text{Lyf}} \), spectral template among template group).

Given the excellent HST (WFPC2, ACS and NICMOS) photometry, \( P(z) \) is quite well defined: the photometric redshift ranges typically between \( z_{\text{phot}} \sim 5.5 \) and 7.3. Outside of the plotted redshift range \( P(z) \) is essentially zero. If we assume the (smaller) quoted formal photometric errors (but note the discrepancies discussed in Sect. 4) \( P(z) \) becomes more peaked, i.e. the photometric redshift better defined. This is driven by the error on the \( z_{\text{50LP}} \) flux, which determines the red side of the “Ly\( \alpha \)” break. However, the resulting best fit value \( z_{\text{phot}} \) does not change much. Furthermore, the fit quality is considerably decreased. This demonstrates the interest of such high accuracy measurements and the need for reliable error estimates.

The predicted redshift distribution is found to be quite insensitive to the exact template (as shown in Fig. 2), to the exact value of \( f_{\text{Lyf}} \), and to the adopted extinction law (variations of the latter two are not shown). However, we note that for this object the fits (and \( P(z) \)) are improved when allowing for deviations from the average Madau (1995) attenuation law. The curves shown here have been computed for \( f_{\text{Lyf}} = 2 \).

More important in determining \( P(z) \) is the exact SED. As seen from Fig. 4 the use of SED1 or SED2 lead to somewhat different \( P(z) \) distributions. SED2 (cf. Sect. 6) yields a somewhat larger redshifts, albeit with a somewhat reduced fit quality. These differences illustrate how uncertainties and difficulties in the photometric measurements of such faint sources, whose origin are briefly discussed in Sect. 6, propagate to the photometric redshift estimate.

All our best-fit solutions have redshift \( z_{\text{phot}} \sim 6.25 – 6.63 \) lower than the redshift range estimated by KESR, but compatible with the more recent quantitative analysis of Egami et al. (2005). Given the various free parameters, uncertainties on the intrinsic SED, etc. we conclude that the redshift of Abell 2218 KESR is likely \( z \sim 6.0 – 7.2 \), taking into account both our photometric determination and the lensing considerations of KESR.
Figure 3. Best fits SEDs to the observations of Abell 2218 (SED2 from Egami et al. 2005, including the flux limit from the non-detections in $V_{606W}$ and at 9000-9300 Å from spectroscopy; cf. Sect. 2). The red crosses indicate the corresponding model broad band fluxes. The solid line shows the best fit for a template from the S03+ group, and dotted from the SB+QSO group. The red-shift for these solutions are $z \sim 6.63$ and 6.54 respectively. See text for more information.

4.2 SED fits and inferences on the stellar population and on Lyα.

A large number of models have been computed using the different variants of the SEDs describing this object (SED1-2), the different filter combinations (non-detections + spectroscopic constraint) discussed in Sect. 2 and varying the various model parameters. We first discuss briefly the main salient results with the help of some illustrations. A more general discussion of the results and their dependence on various assumptions follows.

4.2.1 Age, star formation history, and extinction

Figure 4 shows the best fit models to the SED2 including the upper limits from the $I_{914W}$ and LRIS object spectroscopy for the S03+ and SB+QSO template groups. The best fit redshifts are $z_{\text{phot}} = 6.63$ and 6.54 respectively. These fits show in particular that the spectroscopic constraint can be accommodated simultaneously with the observed $z_{\text{REST}}$ flux; the resulting fits are within the 1 σ errors in all bands. The best fit from the S03+ group corresponds to a burst with an age of 15 Myr at solar metallicity and no extinction (solid line). Similarly good fits are also obtained for lower metallicity. The best fit with empirical starburst and QSO templates (SB+QSO) is obtained with the spectrum of the metal-poor H II galaxy SBS 0335-052 (dotted line in Fig. 4). In this case the apparent Balmer break observed between the NICMOS/HST and IRAC/Spitzer domain is simply explained by the presence of strong emission lines in the 3.6 and 4.5 μm filters \(^3\) and some additional extinction to reduce the restframe UV flux. The extinction needed is $A_V = 0.6$ for the Calzetti et al. law, or $A_V = 0.2$ for the Prévot et al. extinction law. In terms of age the restframe UV to optical spectrum (continuum and lines) of SBS 0335-052 corresponds to a young population of $\sim 3-5$ Myr according to the analysis of Papaderos et al. (1998) and Vanzi et al. (2000). Of course, the presence of an older population in addition to the starburst cannot be excluded on the present grounds. In short, the observed SED of Abell 2218 KESR can be explained by a young population without or with emission lines. Spectroscopy in the 3-4 μm range would be needed to distinguish the latter solution from others.

Alternatively, good SED fits are also obtained with relatively “old” populations. The oldest ages are obtained when invoking the longest SF timescale, i.e. constant SF. In this case the UV restframe flux remains high (due to the continuous formation of massive stars) and older ages need to be attained to build up a sufficient population of evolved stars with strong Balmer breaks, in order to reproduce the observed break. This case is shown in Fig. 4 with fits with the

\(^3\) The main lines are between H$_\gamma$, H$_\beta$ and [O III] $\lambda\lambda$4959,5007 in the 3.6 μm filter and H$\alpha$ $\lambda$6587 in the 4.5 μm filter. E.g. for the emission lines between H$_\gamma$ and [O III] $\lambda\lambda$4959,5007 the total observed equivalent width (boosted by the $(1 + z)$ factor) is $\sim 9130$ Å, as estimated from the data of Izotov & Thuan (1998), compared to a filter surface of $\sim 6600$ Å.
S03+ templates to the observed SED1 and SED2. The best fits solutions obtained here correspond to ages of 500 and 400 Myr, no extinction, and redshifts \( z_{\text{phot}} \sim 6.40 \) and 6.57 respectively. Similar, but somewhat older ages are obtained for metallicities \( Z < 0.008 \), below the ones shown here.

A quantitative examination of the “maximum age” allowed by the observations (here SED2) is presented in Fig. 3 showing \( \chi^2 \) contours in the extinction–age plane for a given set of spectral templates (S03+ group with constant SFR), the Calzetti et al. extinction law, and a fixed redshift of \( z = 6.55 \). For these conditions the best fit is corresponds to 400 Myr, zero extinction, and \( z_{\text{phot}} = 6.57 \) (see Fig. 1). This Figure shows that a maximum age of 250–650 Myr (1 \( \sigma \) interval) is obtained, in good agreement with the modeling of Egami et al. (2005). If true, this would correspond to a formation redshift of \( z_{\text{form}} \sim 8.7–20 \) for our adopted cosmological parameters. As clear from Fig. 3 even with constant SF models, younger populations with some extinction can also fit, although less well, the present observations. However, solutions with low or zero extinction are generally preferred.

When varying the star formation history between these extreme cases (burst or SFR=const), i.e. considering e.g. exponentially declining SF histories, any intermediate age can be found for obvious reasons. Such cases are e.g. obtained when fitting templates from the Bruzual & Charlot models (not shown here) with exponentially decreasing SF histories and can be found in Egami et al. As discussed in Sect.

4.2.2 Ly\( \alpha \) emission

The observations obtained so far have not revealed any emission line from this object (KESR). In particular Ly\( \alpha \) emission is lacking, which could be puzzling for a source with intense star formation. As we have just seen a variety of star formation histories and ages are possible for Abell 2218 KESR. Therefore one may or may not expect intrinsic Ly\( \alpha \) emission.

A simple explanation for the apparent absence of Ly\( \alpha \) emission could be to invoke an advanced age (in the post starburst phase). However, even with a young age it is not necessary that Ly\( \alpha \) emission be observed. E.g. the spectrum of the metal-poor H II galaxy SBS 0335-052 which provides an excellent fit to the observed SED and shows strong emission lines (cf. Fig. 3) does not show Ly\( \alpha \) emission (Thuan et al. 1997, Kunth et al. 2003). Alternatively, if intrinsically present, the Ly\( \alpha \) non-detection could be due a variety of factors: a redshift \( z \lesssim 6.4 \) placing Ly\( \alpha \) below the spectral range discussed in detail by KESR, a flux below their strongly varying detection threshold, or other factors depressing the Ly\( \alpha \) emission within the host galaxy (dust, ISM+HI geometry) and in the intervening IGM.

In conclusion, from the available data the apparent lack of Ly\( \alpha \) emission from this source is not puzzling. However, it is not completely excluded that the galaxy truly shows Ly\( \alpha \) emission, which has so far eluded detection.

4.2.3 General comments on fits and discussion

After these main findings we shall now quickly mention more “technical” results about the influence of various fit parameters.

Quite generally, the results on the age, SF history, extinction etc. depend little on the different variants of the observed SEDs (SED1-2), on the inclusion or not of the non-detections in the fits, and on the use of the published formal errors or a minimum error of 0.15 mag (cf. Sect. 2). The results discussed above are therefore quite robust with respect to these assumptions. Small differences in the best fit values can, however, be obtained. E.g. the best fit photometric redshift can vary by up to \( \lesssim 0.2 \) depending on adopting SED1 or SED2. In all cases we note that SED1 allows better fits (smaller \( \chi^2 \)) than SED2. Adopting \( f_{\text{min}} = 0.15 \) mag also significantly increases the fit quality. Finally, considering variations around the mean Lyman forest attenuation improves the fits (especially as the HST photometry determining the “Ly\( \alpha \) break” is quite accurate). In practice all best fits are found with an increased Lyman-forest opacity (\( f_{\text{Ly} \alpha} = 2 \)).

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1 This is probably excluded as, according to J.-P. Kneib (2005, private communication), no emission line was found in the blue part of the spectrum taken with LRIS.
To summarise, given the absence of a spectroscopic redshift, a fair number of good fits is found to the observations of Abell 2218 KESR when considering all the free parameters. The main conclusions from these “best fits” are:

1) Generally the determined extinction is negligible or zero quite independently of the adopted extinction law. The best fit with the empirical starburst spectrum of SBS 0335-052 represents an exception to this case, requiring an additional $A_V \sim 0.2–0.6$ mag, depending on the adopted extinction law.

2) Although generally burst models fit somewhat better than those with constant star formation among the theoretical templates (BC, S03+), the data does not strongly constrain the star formation history.

3) Typical ages between $\sim 15$ and 400 Myr are obtained. A reasonable 1-sigma upper bound on the age of $\sim 650$ Myr can be obtained assuming constant star formation. However, the data can also be well fit with a very young ($\sim 3–5$ Myr) stellar population with strong emission lines (using e.g. the spectrum of the metal-poor galaxy SBS 0335-052). In this case the apparent Balmer break observed between the HST and Spitzer broad-band photometry is simply due to the presence of strong emission lines affecting the red 3.6 and 4.5 $\mu$m filters.

4) Given degeneracies of the restframe UV spectra between age and metallicity (cf. above) no clear indication on the galaxian metallicity can be derived, in contrast to the claim of KESR. Good fits to the available data can even be found with solar metallicity starburst templates.

5) Depending on the star formation history and age one may or may not expect intrinsic Ly$\alpha$ emission, i.e. an important H II region around the object. The apparent absence of observed Ly$\alpha$ emission does therefore not provide much insight.

A more complete error analysis beyond the level presented here is difficult to achieve for a variety of reasons and clearly beyond the scope of this publication.

### 4.2.4 SFR, stellar mass and luminosity

The theoretical templates can also be used to estimate the stellar mass involved in the starburst or the star formation rate when constant star formation is assumed. For this aim we use all the best fits to the three SEDs (SED1-3) with the S03+ templates, we assume a typical redshift of $z = 6.6$, and the magnification $\mu = 25$ determined by KESR. For the adopted cosmology the distance luminosity is then $d_L = 64455.8$ Mpc.

When constant SF is assumed one obtains the following star formation rate: $SFR \sim (0.9 – 1.1) M_\odot$ yr$^{-1}$ (for a Salpeter IMF from 1 to 100 $M_\odot$). For the best fit ages of $\sim 400–570$ Myr the total mass of stars formed would then correspond to $\sim (3.6 – 6.3) \times 10^8 M_\odot$. The mass estimated from best fit burst models (of ages $\sim 6–20$ Myr) is slightly smaller, $M_* \sim (0.3 – 1) \times 10^9 M_\odot$. If we assume a Salpeter IMF with $M_{low} = 0.1 M_\odot$, the mass and SFR estimates would be higher by a factor 2.55, and in good agreement with the values derived by KESR and Egami et al. (2005). In all the above cases the total luminosity (unlensed) is typically $L_{bol} \sim 2 \times 10^{10} L_\odot$.

### 5 RESULTS FOR ABELL 370 HCM 6A

#### 5.1 SED fits and inferences on the stellar population

Overall the published SED of HCM 6A (see Fig. 7) is “reddish”, showing an increase of the flux from $Z$ to $H$ and even to $K'$5. From this simple fact and the above explanations it is already clear qualitatively that one is driven towards solutions with a) “advanced” age and little extinction or b) constant or young star formation plus extinction. However, a) can be excluded as no Ly$\alpha$ emission would be expected in this case.

Quantitatively, the best solutions obtained for each spectral template group is shown in the left panel of Figure 4. Indeed, the solutions shown correspond to bursts of ages $\sim 50–130$ Myr (BCCWW+, S03 templates) and little or no extinction. However, as just mentioned, solutions lacking young ($\lesssim 10$ Myr) massive stars can be excluded since Ly$\alpha$ emission is observed. The best fit empirical SB+QSO template shown corresponds to the spectrum of the II group galaxy SBS 0335-052 with an additional extinction of $A_V = 1$. To reconcile the observed SED with Ly$\alpha$, a young population, e.g. such as SBS 0335-052, or constant SF is required. In any of these cases fitting the “reddish” SED requires a non negligible amount of reddening.

To illustrate the typical range of possible results we show in Fig. 4 $\chi^2$ contour maps and corresponding confidence intervals for solar metallicity models (S03+ template group) and reddened with the Calzetti law. The left panel (burst models) illustrates in particular the need for progressively higher extinctions the younger the bursts. All ages $\gtrsim 10$ Myr are excluded for the absence of Ly$\alpha$ emission. From the constant SF models (right panel) we see that for a given age $A_V$ is typically $\sim 0.5–1.8$ mag at the 68% confidence level. For obvious reasons, no constraint can be set on the age since the onset of (constant) SF.

Hence, from the photometry of HCM 6A and from the presence of Ly$\alpha$ we are led to conclude that this object must suffer from reddening with typical values of $A_V \sim 1$ for a Calzetti attenuation law. A somewhat smaller extinction ($A_V \sim 0.4$) can be obtained if the steeper SMC extinction law of Prévot et al. (1984) is adopted. From the present data it is not possible to distinguish the different extinction/attenuation laws. Also, it is not possible to draw any constraints on the metallicity of HCM 6A from the available data (cf. Sect. 3.4).

What if we are dealing with composite stellar populations? Indeed it is conceivable that the Ly$\alpha$ emission originates from a population of young stars and the “reddish” restframe UV flux be due to another, older population. Assuming constant SF, no loss of Ly$\alpha$ and standard SFR conversion factors, the observed Ly$\alpha$ emission implies a maximum UV flux of the order of 0.1 $\mu$Jy (and approximately constant in $F_v$ over the observed wavelength range: $\lambda_{rest} \gtrsim 3000$ $\AA$) for an unreddened population. The bulk of the observed flux could then be from an older population. In this case the rising spectrum from the $\varepsilon_{bol}$, over the JH (and presumably K) bands could even be due to an unred-
Stellar populations and Lyα emission in two lensed $z \gtrsim 6$ galaxies

**Figure 6.** Best fits SEDs to the observations of Abell 370 HCM 6A. The red crosses indicate the corresponding model broad band fluxes. Solid lines show the best fit for a template from the BC+CWW group, dotted from SB+QSO group, and dashed from the S03+ group (see explanations in Sect. 3). **Left:** Observed spectral range. **Right:** Predicted SED in Spitzer/IRAC domain for best fit models. Dashed lines show the bursts from the BCCWW+ and S03+ template groups. The dotted line is the spectrum of SBS 0335-052 from the SB+QSO group with additional $A_V = 1$. The solid lines show best fits for constant star formation using different extinction/attenuation laws (Calzetti starburst law versus SMC law). The solid triangles illustrate the IRAC point-source sensitivity (1 σ) for low and medium backgrounds excluding “confusion noise”.

**Figure 7.** $\chi^2$ contour plots showing solutions in extinction – age diagrams. The best solutions are indicated by the black dot. Equidistant $\chi^2$ levels with a spacing of 0.5 are shown. The 2D 68% confidence region (corresponding to $\Delta \chi^2 = 2.3$) is delimited by the solid thick black line. The (1D) 68% confidence region for $A_V$ ($\Delta \chi^2 = 1$) at each given age is delimited by the dashed thick black line. **Left:** Plot for solutions using a solar metallicity burst template from the S03+ template group and the Calzetti attenuation law. Although providing a good fit to the photometry, the region corresponding to ages $\gtrsim 15$ Myr, right of the dotted vertical line, is excluded as no emission line would be expected in this case. **Right:** Same as left panel for constant star formation models. The solutions indicate a non-negligible extinction, but no constraint on age. Discussion in text.
dened population; a strongly increasing flux and probably a significant “Balmer” break is then expected, similar to the aged burst shown in the right panel of Fig. 6. This explanation should in principle be testable with Spitzer observations as discussed below.

How does our possible indication for a high extinction fit in with other studies? At redshift $z \lesssim 4$ the extinction of Lyman break galaxies (LBGs) has been estimated by various authors (e.g. Savicky & Yee 1998, Meurer et al. 1999, Adelberger & Steidel 2000, Shapley et al. 2001, Ouchi et al. 2004). Given their mean/median values (typically $< E(B-V) > \sim 0.15-0.2$) and the $E(B-V)$, our finding of a “high” extinction is not exceptional. Furthermore, Armus et al. (1998) find indications for $A_V > 0.5$ mag from their analysis of a $z = 5.34$ galaxy. However, this implies that dust extinction is likely present in starburst galaxies with redshifts above 6. Large amounts of dust have already been observed in QSOs up to similar redshift (Bertoldi et al. 2003, Walter et al. 2003).

### 5.2 Properties of HCM6A: SFR, mass, Lyα transmission

To estimate properties such as the mass, SFR, and the intrinsic Lyα emission from HCM 6A we simply examine the predictions from the best fit models, scale them appropriately to the luminosity distance6, and correct for the gravitational magnification (here $\mu = 4.5$). The derived quantities are summarised in Table I.

First we consider single (non-composite) stellar populations. From the best fit constant SF models (with variable ages) we deduce an extinction corrected star formation rate of the order of $\text{SFR(UV)} \sim 11 - 41 \, M_\odot \, \text{yr}^{-1}$ for a Salpeter IMF from 1 to 100 $M_\odot$. For a commonly adopted, although unjustified, Salpeter IMF down to 0.1 $M_\odot$ this would increase by a factor 2.55. Actually this estimate is not very different than the one obtained from standard SF calibrations provided the same assumptions on the IMF. Indeed the observed restframe UV luminosity, e.g. derived from the average J, H, and K’ flux of $F_{\text{UV}} = (2.6 \pm 0.7) \times 10^{-30}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ is $L_{\text{restUV}} = 4 \pi d_L^2 F_{\text{UV}}/(1+z)/\mu \approx 4 \times 10^{28}$ erg s$^{-1}$ Hz$^{-1}$ (Hu et al. 2002), translates to $SFR_{\text{UV}} \approx c L_{\text{restUV}} 10^{0.4(A_V)}$, where $c$ is the usual SFR conversion coefficient, and $A_V$ the UV extinction. For the standard value $c = 1.4 \times 10^{-28}$ from Kennicutt (1998), assuming a Salpeter IMF down to 0.1 $M_\odot$, and $A_{\text{UV}} \sim 2-3$, one has $SFR \sim 35-88 \, M_\odot \, \text{yr}^{-1}$; for the IMF used in this work (Salpeter from 1-100 $M_\odot$) this becomes $SFR \sim 14-34 \, M_\odot \, \text{yr}^{-1}$. This assumption, and the absence of extinction correction also explains the difference with $SFR$ estimate of Hu et al. (2002)7.

For continuous SF over timescales $t_{\text{SP}}$ longer than ~10 Myr, the total (bolometric) luminosity output is typically $\sim 10^{40}$ $L_\odot$ per unit SFR (in $M_\odot$ yr$^{-1}$) for a Salpeter IMF from 1-100 $M_\odot$, quite independently of metallicity. The total luminosity associated with the observed SFR is therefore $L \sim (1-4) \times 10^{11} L_\odot$, close to or just above the limit to possibly qualify as a luminous infrared galaxy ($L_{\text{IR}} > 10^{11} L_\odot$; cf. Sanders & Mirabel 1996) if a significant fraction of its bolometric flux emerges in the (restframe) IR. For $t_{\text{SP}} \sim 10$ Myr the estimated stellar mass is $M_* \approx t_{\text{SP}} \times SFR \sim (1-4) \times 10^8 M_\odot$.

From the data given by Hu et al. (2002), the observed Ly$\alpha$ flux is $F(\text{Ly} \alpha) = \mu \times 3.8 \times 10^{-18}$ erg s$^{-1}$ cm$^{-2}$, with the magnification factor $\mu$. The Ly$\alpha$ luminosity per unit SFR from the same S03 models used above is $L(\text{Ly} \alpha) = (2.4 - 4.4) \times 10^{42}$ erg s$^{-1}$ ($M_\odot$ yr$^{-1}$)$^{-1}$ for metallicities between solar and 1/50 Z$_\odot$. The SFR deduced from Ly$\alpha$ would then be $SFR(\text{Ly} \alpha) \sim 0.4-0.8 \, M_\odot$ yr$^{-1}$ for HCM 6A. Taking an extinction of $A_V = 1.$ (for the Calzetti law) into account implies a reddening corrected SFR(\text{Ly} $\alpha) \sim 7-12 \, M_\odot$ yr$^{-1}$. The ratio between SFR(\text{Ly} $\alpha)/$SFR(UV) presumably reflects the incomplete Ly$\alpha$ transmission $t_{\text{Ly} \alpha}$, which can be estimated in various ways. The most consistent estimate is obtained from the comparison of the predicted Ly$\alpha$ luminosity of each best fit model (obtained from fitting the broad-band SED) to the observed Ly$\alpha$ luminosity. From the best fit models with $A_V \sim 1$ and the Calzetti law we obtain $t_{\text{Ly} \alpha} \sim 23-54 \%$; in the case of the fit with the Prévot

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6 For the adopted cosmology and $z = 6.56$ one has $d_L = 64005.7$ Mpc.

7 Actually Hu et al. (2002) derive without further explanation $SFR = 9 \, M_\odot$ yr$^{-1}$ from $L_{\text{restUV}} = 4 \times 10^{28}$ erg s$^{-1}$, whereas the classical Kennicutt (1998) calibration would yield $SFR = 5.6 \, M_\odot$ yr$^{-1}$ without extinction correction.
et al. extinction law we find a higher transmission \( t_{\text{Ly}\alpha} \approx 90\% \). For comparison Haiman (2002) assumed a Ly\( \alpha \) transmission of 20\% from the data of Hu et al. Per definition this Ly\( \alpha \) “transmission” corresponds to the ratio of the expected/intrinsic Ly\( \alpha \) emission from the starburst over the observed one. The physical causes for a partial (i.e. < 100\%) transmission are of course open to various interpretations (e.g. physical processes destroying Ly\( \alpha \) photons in the host galaxy, absorption in the intervening IGM etc.). In fact the relatively high Ly\( \alpha \) transmission estimated here could be somewhat surprising, given the Gunn-Peterson trough observations in \( z \gtrsim 6 \) quasars (cf. Becker et al. 2001, Fan et al. 2003) and the possible presence of dust (this work).

Consider now the case of composite stellar populations. In this case we retain as a rough estimate in Table 1 the SFR(Ly\( \alpha \)) (from the young population) as a lower limit, and the mass and total luminosity is derived from the best fit burst model of age \( \approx 100 \) Myr assuming that this “older” population dominates the observed continuum flux. Formally we then have no handle on the Ly\( \alpha \) transmission, except that it cannot be very low (say \( \lesssim 40\% \approx 0.1/0.26 = F_{\text{young}} < F_{\text{obs}} > \)) since otherwise the associated UV flux from the young population \( F_{\text{young}} \) would dominate the observed continuum flux \( < F_{\text{obs}} > \).

5.3 Spitzer Observatory predictions

It is interesting to examine the SEDs predicted by the various models at longer wavelengths, including the rest-frame optical domain, which is potentially observable with the sensitive IRAC camera onboard the Spitzer Observatory and other future missions. In the right panel of Fig. 8 we plot the 3 best fits to the observed data for the BCCWW+ and S03+ template groups (“burst” solutions with no extinction) and the SBS 03352-052 template (with additional \( A_V = 1 \)) showing strong optical emission lines. We see that these solutions have fluxes comparable to or above the detection limit of IRAC/Spitzer 8. On the other hand the strongly reddened constant SF or young burst solutions do not exhibit a Balmer break and are hence expected to show fluxes just below the IRAC sensitivity at 3.6 \( \mu \)m and significantly lower at longer wavelengths. As Ly\( \alpha \) emission is expected only for the reddened SEDs the latter solutions (low 3.6-4.5 \( \mu \)m flux) are predicted to apply to HCM 6A, except if composite stellar populations are considered. Indeed, a high 3.6 and 4.5 \( \mu \)m flux could be a good indication for a composite stellar population, as discussed above. In addition it is important to secure higher accuracy photometry especially in the near-IR (JHK) to assess the accuracy of the redward increasing shape of the spectrum (in \( F_{\nu} \)), which drives one towards solutions with non-negligible extinction.

6 CONCLUSION

Using SED fitting techniques considering a large number of parameters (mainly a vast library of empirical and theoretical template spectra, variable extinction and extinction laws) we have attempted to constrain the properties of the stellar populations and Ly\( \alpha \) emission of two strongly lensed galaxies with redshifts \( z \gtrsim 6 \) from their observed SED including various ground-based observations, HST, and Spitzer observations.

The following main results have been obtained for these objects (see Sects. 3-4), and summary in Table 1:

- **Triple arc in Abell 2218** discovered by Kneib et al. (2004, KESR). The most likely redshift of this source is \( z \approx 6.0-7.2 \) taking into account both our photometric determination and lensing considerations.

  SED fits indicate generally a low extinction \( (E(B-V) \lesssim 0.05) \) but do not strongly constrain the SF history. Best fits have typical ages of \( \sim 3 \) to 400 Myr. A reasonable maximum age of (250–650) Myr (1 \( \sigma \) interval) can be estimated. However, the apparent 4000 Å break observed recently from combination of IRAC/Spitzer and HST observations, can also equally well be reproduced with the template of a young (\( \sim 3–5 \) Myr) burst where strong restframe optical emission lines enhance the 3.6 and 4.5 \( \mu \)m fluxes.

  - The estimated SFR is typically \( \sim 1 \) M\(_{\sun}\) yr\(^{-1}\) for a Salpeter IMF from 1-100 M\(_{\sun}\), in agreement with previous estimates.
  - Given the poor constraint on age and SF history, we conclude that intrinsic Ly\( \alpha \) emission may or may not be present in this galaxy. The apparent non-detection of Ly\( \alpha \) by KESR can therefore even be understood without invoking Ly\( \alpha \) destruction.

- **Abell 370 HCM 6A** discovered by Hu et al. (2002). The relatively red SED and the presence of Ly\( \alpha \) emission indicate basically two possible solutions: 1) a young burst or ongoing constant SF with non-negligible extinction \( (A_V \sim 0.5-1.8 \text{ at a } 1 \sigma \text{ level}) \) or 2) a composite young + “old” stellar population.

  - For the first case, best fits are obtained for constant SF with \( E(B-V) \sim 0.25 \). In consequence previous SFR estimates for this source must likely be revised upward. If correct, the bolometric luminosity of this galaxy is estimated to be \( L \sim (1–4) \times 10^{11} L_{\odot} \), comparable to the luminosity of infrared luminous galaxies. Furthermore a Ly\( \alpha \) transmission of \( \sim 23–90\% \) is estimated from our best fit models.

  - Alternatively the observed 0.9-2.2 \( \mu \)m SED could also be fit without extinction by a composite “young” and “old” stellar population, where the former would be responsible for the Ly\( \alpha \) emission and a fraction of the restframe UV flux. The SFR, stellar mass, and total luminosity are then lower than in case 1. The two scenarios may be distinguishable with IRAC/Spitzer observations at 3.6 and 4.5 \( \mu \)m.

  - Given the limited observed spectral range, the present data does not allow to draw any firm constraints on the maximum age of the stellar population.

  In general it should also be noted that broad-band SED fits or measurements of the UV slope do not allow one to determine the metallicity of a star forming galaxy from a theoretical point of view and in terms of individual objects given important degeneracies (cf. Sect. 3.4).
can in principle be used to constrain the intervening IGM properties, and therefore probe the reionisation of the Universe.

Although the results obtained here from this exploratory study of just two lensed galaxies, the highest known redshift galaxies with photometric detections in at least 3–4 filters, cannot provide a general view on the SF and IGM properties at $z \gtrsim 6$, there is good hope that the sample of such objects will considerably increase in the near future with the availability of large ground-based telescopes and sensitive space borne observatories such as Spitzer and even more so with the planned JWST.

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