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Stellar Populations and Lyα Emission from Lensed $z \gtrsim 6$ Galaxies

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Abstract. We present results from an SED analysis of two lensed high-z objects, the $z = 6.56$ galaxy HCM6A behind the cluster Abell 370 discovered by Hu *et al.* (2002) and the triple arc at $z \sim 7$ behind Abell 2218 found by Kneib *et al.* (2004). For HCM 6A we find indications for the presence of dust in this galaxy, and we estimate the properties of its stellar populations (SFR, age, etc.), and the intrinsic Lyα emission. From the "best fit" reddening ($E(B-V) \sim 0.25$) its estimated luminosity is $L \sim (1-4) \times 10^{11} L_{\odot}$, in the range of luminous infrared galaxies. For the arc behind Abell 2218 we find a most likely redshift of $z \sim 6.0$–7.2 taking into account both our photometric determination and lensing considerations. SED fits indicate generally a low extinction but do not strongly constrain the SF history. Best fits have typical ages of ~ 3 to 400 Myr. The apparent 4000 Å break observed recently by Egami *et al.*(2004) from combination of IRAC/Spitzer and HST observations can also well be reproduced with templates of young populations ($\sim$ 15 Myr or even younger) and does not necessarily imply old ages. Finally, we briefly examine the detectability of dusty lensed high-z galaxies with Herschel and ALMA.

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 2003) 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 formation rate (SFR) assuming standard conversion factors between the UV restframe light and the SFR, and nothing is known about the extinction, and the properties of the stellar population (such as age, detailed star formations history etc.)

At higher redshift ($z \gtrsim 6$) even less information is generally available. Many objects are found by Lyα 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 Lyα luminosity can be determined and used to estimate a SFR using again standard conversion factors. Also the Lyα equivalent width is estimated, providing some possible clue on the nature of these source. However, this has lead to puzzling results e.g. for the sources from the LALA survey (Malhotra & Rhoads 2001, Rhoads *et al.* 2003) leaving largely open the question of the nature of these objects, their stellar populations, extinction etc.

Strong gravitation lensing is extremely "helpful" for a large number problems discussed at this conference, including also the present one. In particular strong lensing has allowed to detect several of the highest redshift galaxies known today (e.g. Ellis *et al.* 2001, Hu *et al.* 2002, Kneib *et al.* 2004, Pelló *et al.* 2004a, and the review of Pelló *et al.* 2003). Also, thanks to the lensing magnification, it has been possible to obtain photometric observations of reasonable quality in several bands for some of these objects. For example it has even very recently been possible to image a $z \sim 7$ galaxy with the Spitzer observatory at 3.6 and 4.5 μm (Egami *et al.* 2004) ! As we'll show below (Sects. 2 and 3) this allow us to perform a quantitative SED analysis to constrain properties of the stellar populations, such as age and star formation (hereafter SF) history (burst or constant SF?), their extinction, intrinsic Lyα emission etc. A detailed account of this work will be published elsewhere (Schaerer & Pelló 2004).

As such, gravitational lensing provides a unique opportunity to learn more about some selected high-z galaxies. If generalised and applied to larger samples in the near future, systematic studies of the properties of lensed high-z galaxies could provide unique insights and complementary information to other deep/ultra-deep surveys targetting blank fields. Also, extensions to wavelengths beyond the optical and near-IR with existing facilities (e.g. in the radio, mm, and possibly sub-mm) and future observatories should be of great interest, as briefly outlined for Herschel and ALMA in Sect. 4.

2. Stellar populations and dust in a lensed $z = 6.56$ starburst galaxy

The lensed $z = 6.56$ galaxy HCM6A was found by Hu *et al.* (2002) from a narrow-band survey in the field of the lensing cluster Abell 370. Its redshift is established from the broad-band SED including a strong spectral break, and from the observed asymmetry of the detected emission line identified as Lyα.

We have recently analysed the SED of this object by means of quantitative SED fitting techniques using a modified version of the *Hyperz* code of Bolzonella *et al.* (2000) †. The observed $VRIZJHK'$ data are taken from Hu *et al.* (2002). The gravitational magnification of the source is $\mu = 4.5$ according to Hu *et al.* The main free parameters of the SED modeling are the spectral template, extinction, and the reddening law. Empirical and theoretical templates including in particular starbursts and QSOs (SB+QSO templates), and predictions from synthesis models of Bruzual & Charlot (BC+CWW group) and from Schaerer (2003, hereafter S03) are used.

Overall the SED of HCM 6A (see Fig. 1) is "reddish", showing an increase of the flux from Z to H and even to K‡. From this simple fact it is already clear qualitatively that one is driven towards stellar populations with a) "advanced" age and little extinction or b) constant or young star formation plus extinction. However, for HCM6A a) can be excluded as no Lyα emission would be expected in this case.

Quantitatively, the best solutions obtained for three "spectral template groups" are shown in the left panel of Fig. 1. The solutions shown correspond to bursts of ages $\sim$ 50–130 Myr and little or no extinction. However, as just mentioned, solutions lacking young ($\lesssim$ 10 Myr) massive stars can be excluded since Lyα emission is observed. The best fit empirical SB+QSO template shown corresponds to the spectrum of a metal-poor starburst galaxy with an extinction of $A_V \sim 1$. On the basis of the present observations a narrow line (type II) AGN cannot be ruled out. To reconcile the observed SED with

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

‡ The significance of a change of the SED slope between JH and HK seems weak, and difficult to understand.

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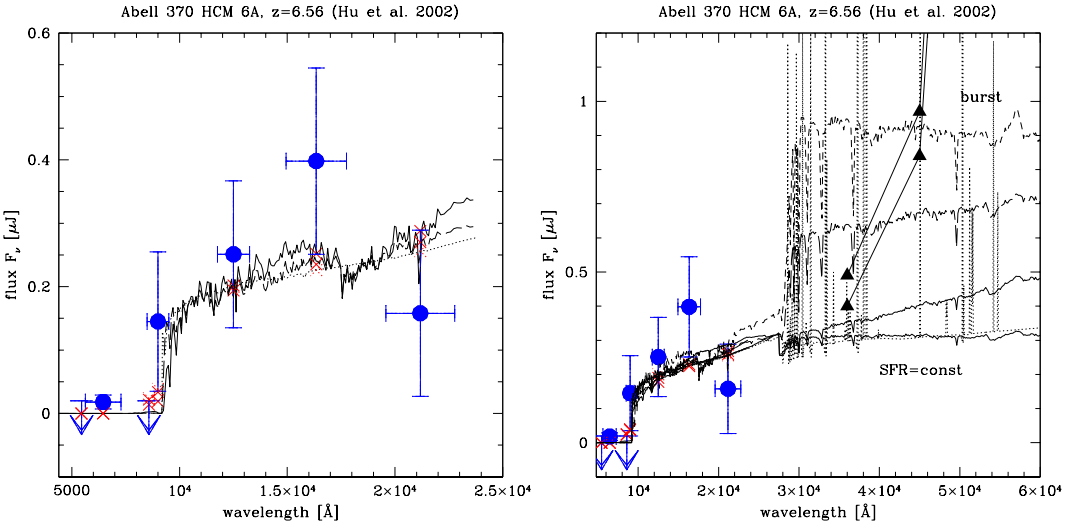

Figure 1. Best fits SEDs to the observations of Abell 370 HCM 6A. The red crosses indicate the corresponding model broad band fluxes. Solid lines show the best fit for a template from the BC+CWW group, dotted from SB+QSO group, and dashed from the S03+ group **Left:** Observed spectral range. **Right:** 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 1is 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".

Lyα, a young population or constant SF is required. In any of these cases fitting the "reddish" SED requires a non negligible amount of reddening.

Although all best fit models require reddening, this result is at present indicative and need to be firmed up. Quantitatively (e.g. for constant star formation, solar metallicity models, Calzetti law) A_V is typically $\sim$ 0.5–1.8 mag at the 68 % confidence level. Also somewhat smaller extinction can be obtained if the steeper SMC extinction law of Prévot *et al.* (1984) is adopted. Zero extinction cannot be ruled out at the $\sim 2\sigma$ level. Better photometric accuracy, especially in the JHK bands, is needed to reduce the present uncertainties and hence confirm the indication for dust.

From the best fit constant SF models we deduce an extinction corrected star formation rate of the order of SFR(UV) $\sim 11 - 41$ M$_\odot$ yr^{-1} for a Salpeter IMF from 1 to 100 M$_\odot$ or a factor 2.55 higher for the often adopted lower mass cut-off of 0.1 M$_\odot$. For continuous SF over timescales $t_{\rm SF}$ longer than $\sim$ 10 Myr, the total (bolometric) luminosity output is typically $\sim 10^{10}$ 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 SF is therefore $L \sim (1-4) \times 10^{11} L_\odot$, in the range of luminous infrared galaxies (LIRG). For $t_{\rm SF} \sim 10$ Myr the estimated stellar mass is $M_\star \approx t_{\rm SF} \times SFR \sim (1-4) \times 10^8$ M$_\odot$. Other properties such as the "Lyα transmission" can also be estimated from this approach. A relatively high Lyα transmission of $\sim$ 20–50 % but possibly up to $\sim$ 90 % is estimated from our best fit models (see Schaerer & Pelló 2004).

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. 1 we plot again the 3 best fits. We see that these solutions have

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fluxes comparable to or above the detection limit of IRAC/Spitzer †. 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 μm and significantly lower at longer wavelengths. As Lyα emission is expected only for the reddened SEDs the latter solutions are predicted to apply to HCM 6A. If possible despite the presence of other nearby sources, IRAC/Spitzer observations of HCM 6A down to the detection limit or observations with other future satellites could allow to verify our prediction and therefore provide an independent (though indirect) confirmation of the presence of dust in this high-z galaxy.

3. A lensed galaxy at $z \sim 6$–7 behind Abell 2218

This interesting triply imaged object, a possible $z \sim 7$ galaxy, has recently been discovered by Kneib *et al.* (2004, hereafter KESR) from deep Z band observations with ACS/HST. In the meantime it has also been observed with Spitzer (see Richard *et al.*, these proceedings; Egami *et al.* 2004). The currently available observations include V_{606W}(undetected), I_{814W}, z_{850LP}, J, H_{110W}, H_{160W}, and 3.6 and 4.5 μm with IRAC/Spitzer. The photometry from these authors has been adopted here to analyse the properties of this object in a similar way as for HCM 6A. In practice, small differences are found in the published photometry; we therefore adopt three different SEDs (SED1-3) to describe this object (see Schaerer & Pelló 2004 for details). 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 $z \sim 6.5$–7 for this source. The magnification factors of both images a and b is $\mu = 25 \pm 3$, according to KESR.

As a spectroscopic redshift has not been obtained (yet) for this galaxy we here examine its photometric redshift estimate. In Fig. 2 (left) we show the photometric redshift probability distributions $P(z)$ for the three SEDs (SED1-3) of Abell 2218 KESR using 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, $f_{\rm Lyf}$, spectral template amoung template group). Given the excellent HST (WFPC2, ACS and NICMOS) photometry, $P(z)$ is quite well defined: the photometric redshift ranges typically between $z_{\rm phot} \sim 5.5$ and 7.3. Outside of the plotted redshift range $P(z)$ is essentially zero.

To summarise (but cf. Schaerer & Pelló 2004), 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. Three of them are illustrated in Fig. 2 (right). The main conclusions from these "best fits" are:

1) Generally the determined extinction is negligible or zero quite independently of the adopted extinction law. For few empirical templates we find good fits 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, the data does not strongly constrain the star formation history.

3) Typical ages between ~ 15 and 400 Myr are obtained. A reasonable 1-σ upper bound on the age of $\sim$ 650 Myr can be obtained assuming constant star formation. Young solutions ($\sim$ 15 and even younger) are obtained with burst models or some empirical

† See `http://ssc.spitzer.caltech.edu/irac/sens.html`

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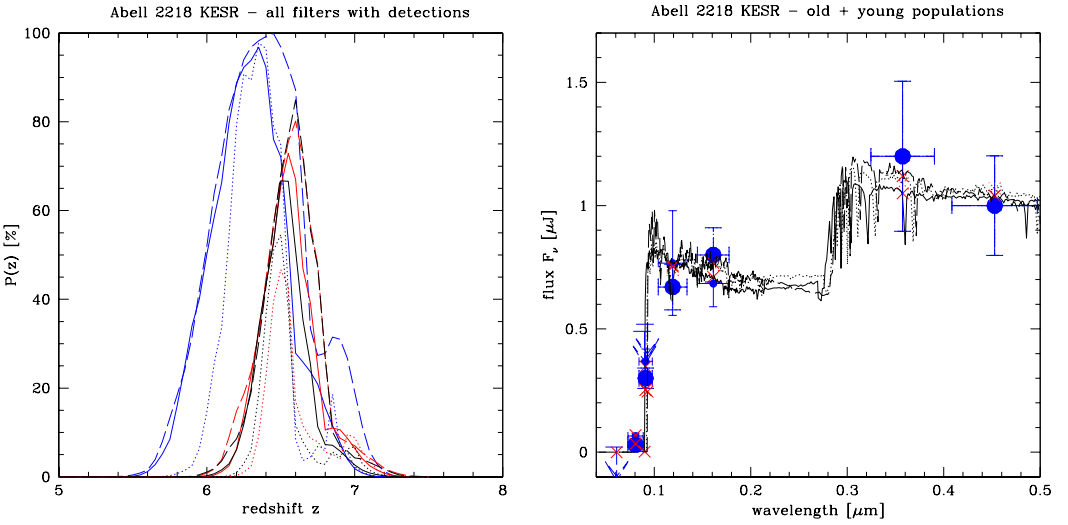

Figure 2. Left: Photometric redshift probability distributions $P(z)$ of Abell 2218 KESR using three spectral template groups (solid, dotted, long dashed), three different variants of the SED, and the photometry from all filters in which the object is detected (I_{814W} to 4.5 μm) assuming a minimum photometric error of 0.15 mag. **Right:** Best fits SEDs to the observations of Abell 2218 from Egami *et al.* 2004 (SED2) 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 redshift for these solutions are $z \sim 6.63$ and 6.54 respectively. See text for more information

templates. The relatively modest strength Balmer break observed between the HST and Spitzer broad-band photometry does not necessarily imply old ages.

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 Lyα emission, i.e. an important H II region around the object. The apparent absence of observed Lyα emission does therefore not provide much insight.

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 assume a typical redshift of $z = 6.6$, and the magnification $\mu = 25$ determined by KESR. For constant SF we obtain $SFR \sim (0.9 - 1.1)$ $M_\odot$ 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, $M_\star \sim (0.3 - 1) \times 10^8$ $M_\odot$. 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.*. In all the above cases the total luminosity (unlensed) is typically $L_{bol} \sim 2 \times 10^{10}$ $L_\odot$.

4. $z \gtrsim 6$ starbursts: with Herschel and ALMA, and now ...

Let us now assume that starburst galaxies with dust exist at $z \gtrsim 6$ and briefly examine their observability with facilities such as Herschel and ALMA. To do so we must assume a typical galaxy spectrum including the dust emission. For simplicity we here adopt the

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SED model by Melchior *et al.* (2001) based on PEGASE.2 stellar modeling, on the Désert *et al.* (1990) dust model, and including also synchrotron emission. Their predicted SED for a galaxy with an SFR and/or total luminosity quite similar to that estimated above for HCM6A is shown in Fig. 3.

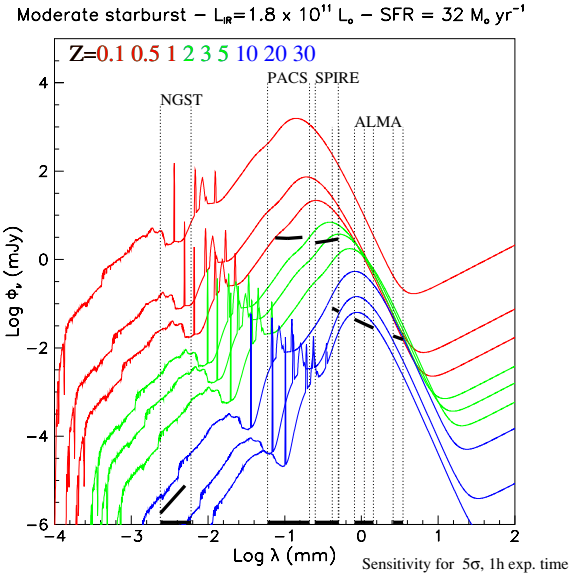

Figure 3. Predicted spectrum for a "moderate" starburst with SFR=32 $M_\odot$ yr^{-1} and $L \sim 1.8 \times 10^{11} L_\odot$ placed at redshift z =0.1, 0.5, 1, 2, 3, 5, 10, 20, and 30. The thresholds of the JWST (here NGST), PACS and SPIRE onboard Herschel, and ALMA are also presented. Figure taken from Melchior *et al.* (2001) with kind permission

Figure 3 shows the exquisite sensitivity of ALMA in the various bands allowing in principle an easy detection of such objects up to redshift ~ 10 or even higher!

On the other hand, with the sensitivity of PACS and SPIRE on Herschel blank field observations of such an object are limited to smaller redshift ($z \lesssim$ 1–4). However, already with a source magnification of $\mu \sim$ 3–10 or more the "template galaxy" shown in Fig. 3 becomes observable with SPIRE at $\sim$ 200–670 μm. In fact, such magnifications (and even higher ones) are not exceptional in the central parts of massive lensing clusters. E.g. in our near-IR search conducted in two ISAAC fields ($\sim$ 2.5x2.5 arcmin^2) of two lensing clusters, a fair number ($\sim$ 10–20) of $z \gtrsim$ 6–7 galaxy candidates with $\mu \gtrsim 5$ are found (Pelló *et al.* 2004b and these proceedings, Richard *et al.* 2004, in preparation). More than half of them have actually magnifications $\mu \gtrsim 10$. Such simple estimates show already quite clearly the potential of strong gravitational lensing to extend the horizon of SPIRE/Herschel observations beyond redshift $z \gtrsim 5$!

Obviously a more rigorous feasibility study must also address the following issues: How frequent is dust present in high-z galaxies? and up to what redshift? We now have some indications for dust in one lensed $z = 6.56$ galaxy (see Section 2) and of course in high-z quasars. But how general/frequent is this? How typical is the SED adopted above? The long wavelength emission due to dust depends on various parameters such as metallicity, the dust/gas ratio, geometry, the ISM pressure etc. Furthermore spatial resolution and source confusion are key issues which must be addressed and which should vary quite strongly between blank fields and cluster environments. Last, but not least, the field

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of view of the various instruments is determinant for the efficiency with which high-z candidates can be found and studied. Several of these issues have already been partly addressed earlier (cf. the 2000 Herschel conference proceedings of Pilbratt *et al.* 2001, also Blain *et al.* 2002).

It is evident that various ground-based and space bourne facilities and instruments will be used together to provide an optimal coverage in wavelength, spatial resolution and field size, and to obtain imaging as well as spectroscopy. Near-IR wide field imagers and near-IR multi-object spectrographs on 8-10m class telescopes and later with ELTs will undoubtably "team up" with the JWST, Herschel and ALMA to explore the first galaxies in the Universe and their evolution from the Dark Ages to Cosmic Reionisation. The wonderful power offered by gravitational lensing will continue to provide deeper or "enhanced" views of prime interest for the exploration of the early Universe.

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