The SED of the lensed $z = 6.56$ galaxy HCM6A behind the cluster Abell 370 has been analysed. We find clear indications for the presence of dust in this galaxy, and we estimate the properties of its stellar populations (SFR, age, etc.). From its estimated luminosity, $L \sim (1 - 4) \times 10^{12} L_\odot$, this galaxy ranks as a luminous infrared galaxy. This case is then used to examine the detectability of high-$z$ galaxies with Herschel and ALMA. It is evident that with the use of strong gravitational lensing SPIRE/Herschel observations could provide very interesting information on $z > 5$ galaxies. Strong synergies between ground-based near-IR instruments on 8-10m class telescopes and ELTs, Herschel, the JWST, and ALMA can be expected for the exploration of the first galaxies in the Universe.

Key words: Galaxies: starburst – Gravitational lensing – early Universe – Infrared: galaxies – Submillimeter.

1. INTRODUCTION

Considerable advances have been made in the exploration of the high-$z$ Universe during the last decade, starting with the discovery and detailed studies of redshift $z \sim 3$ galaxies (Lyman break galaxies, LBGs), mostly from the pioneering work of Steidel and collaborators (cf. Steidel et al. 2003), reaching over the $z \sim 4-5$ galaxies from different deep multi-wavelength surveys, up to galaxies at $z \sim 6-7$ close to the end of the reionisation epoch of the Universe (e.g. Kodaira et al. 2002, Hu et al. 2002, Cuby et al. 2003, Kneib et al. 2004, Stanway et al. 2004, Bouwens et al. 2004). To extend the present searches beyond $z \geq 6.5$ and back to ages where the Universe was being re-ionized (cf. Fan et al. 2002), it is mandatory to move into the near-IR bands. This logical extension should allow to find and study the galaxies up to $z \sim 10$ with ground based instruments and telescopes.

Other approaches could also be used to search for galaxies during the re-ionisation epoch. Indeed, the recognition of a large negative k-correction of dust emission in the sub-mm and mm regime which largely overcomes the effect of the inverse square law and cosmological surface brightness dimming, and the existence of numerous dust rich galaxies up to fairly high redshift, indicate that searches with high resolution instruments as ALMA could locate high-$z$ galaxies in an independent way and probably even measure their redshift from fine structure lines (see e.g. Blain et al. 2000, Guiderdoni et al. 1999). However, to be feasible such searches obviously require that the target galaxies are chemically evolved and contain sufficient dust. Although quasars up to the highest redshift currently known have revealed the presence of important quantities of dust (e.g. at $z = 6.42$, Walter et al. 2004), little is known about dust in galaxies above $z \gtrsim 5$. Actually most observations of Lyman break galaxies (LBG) at $z > 4$ seem to show relatively blue colors (and bluer ones than LBGs at lower $z$), which possibly indicates less/littlereddening in these objects (see e.g. Stanway et al. 2004, Bouwens et al. 2004, review of Schaerer 2004). Finding $z \gg 4$ galaxies with significant amounts of dust, and more generally studying the dust properties and content in high-$z$ objects is therefore of great interest.

Here we first report on a recent analysis of a lensed $z = 6.56$ starburst galaxy indicating the presence of significant dust extinction (Schaerer & Pelló 2004). We then use this case to illustrate the detectability of such objects with Herschel and ALMA, in particular in conjunction with strong gravitational lensing.
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 the 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 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 (1σ) for low and medium backgrounds excluding “confusion noise”.

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 μ = 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 ~ 50–130 Myr and little or no extinction. However, as just mentioned, solutions lacking young (~ < 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 the H II galaxy SBS 0335-052 with an additional extinction of A_V = 1. On the basis of the present observations a narrow line (type II) AGN cannot be ruled out. To reconcile the observed SED with Lyα, 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. 2 χ^2 a contour map and the correspond-

1The significance of a change of the SED slope between JH and HK seems weak, and difficult to understand.
Figure 2. $\chi^2$ 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. Plot for solutions using a solar metallicity burst template from the S03+ template group and the Calzetti attenuation law. The solutions indicate a non-negligible extinction, but no constraint on age. Discussion in text.

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 $t_{SF}$ 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 $t_{SF} \sim 10$ Myr the estimated stellar mass is $M_* \approx t_{SF} \times SFR \sim (1 - 4) \times 10^8$ M$_\odot$. Other properties such as the “Ly$\alpha$ transmission” can also be estimated from this approach (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 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 Ly$\alpha$ 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. $Z \gtrsim 6$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 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 shows the exquisite sensitivity of ALMA in the various bands allowing in principle an easy detection of such objects up to redshift $\sim 10$ or even higher!

On the other hand, with the sensitivity of PACS and SPIRE 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

\footnote{See \url{http://ssc.spitzer.caltech.edu/irac/sens.html}}
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 undoubtedly “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.

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