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ABSTRACT

The gravitationally lensed Lyα emitting galaxy, HCM 6A, detected by Hu et al. (2002) at z=6.56 behind the Abell 370 cluster was observed with the MAMBO-2 array of bolometers at 1.2 mm wavelength. The galaxy was not detected down to 1.08 mJy (3σ), but the depth of the observations and the lens amplification allow us to improve by approximately one order of magnitude previously published upper limits on far infrared emission of Lyα emitting galaxies at this redshift.
The following upper limits are derived from our observations assuming typical dust parameters: dust mass $< 5.3 \times 10^7$ M$_\odot$, IR luminosity $< 2.1 \times 10^{11}$ L$_\odot$, and star formation rate < 35 M$_\odot$ yr^{-1}. The observed restframe UV–optical–IR spectral energy distribution (SED) of this galaxy is compatible with that of normal spiral galaxies or blue compact dwarf galaxies. SEDs of prototypical ULIRGs, such as Arp 220, are clearly excluded. Finally, we obtain an upper limit of $\lesssim 2.1 \times 10^{-2}$ M$_\odot$ yr^{-1} Mpc^{-3} for the dust-obscured SFR density of Lyα selected galaxies at $z \sim$ 6.6.

Key words. galaxies: formation – galaxies: high redshift – galaxies: clusters: lensing

1. Introduction

Nine of the 22 QSOs known to date at z~6 (Fan 2006; Willott et al. 2007) were detected at millimeter wavelengths (Priddey et al. 2003; Bertoldi et al. 2003a; Robson et al. 2004; Wang et al. 2007). The infrared luminosities implied by the millimeter fluxes are typically 10^{13} L$_\odot$ and the dust masses are $> 10^8$ M$_\odot$. In addition, CO lines were detected in J1148+5251 (Bertoldi et al. 2003b; Walter et al. 2003) revealing a large amount of dense molecular gas (2.2×10^{10} M$_\odot$) most probably heated by a starburst rather than by an AGN. The Gunn-Peterson trough seen in the optical spectrum of these objects indicate that they are situated at the end of the epoch of reionisation (Loeb & Barkana 2001). These observations imply that the process of enrichment of the ISM is relatively advanced in these objects and could have started at $z \gtrsim 8$. This is in agreement with the results of WMAP which place the first onset of star formation at $z \gtrsim 11$ (Page et al. 2006). These observations also put into question the processes responsible for the dust formation. Indeed, at the redshift of J1148+5251 the Universe was only $\sim$ 0.8 Gyr old and dust formation in quiescent winds of low mass stars would not have been efficient enough to produce the observed masses. Possible sources of enrichment are SNII or pair instability SN (e.g. Todini & Ferrara 2001; Schneider et al. 2004), which can explain several observations in the QSOs at $z \sim 6$ (Venkatesan et al. 2004). Quasar winds may also be a source of dust production. To better understand the dust formation mechanisms and to obtain a more global view of star formation in the early Universe it is essential to observe $z > 6$ non-quasar galaxies in the submillimeter range. To date submillimeter observations of only two galaxies at $z > 6$ have been reported in the literature (Webb et al. 2007), and each new observation brings important constraints to the models.

The $z = 6.56$ galaxy HCM6A was discovered by Hu et al. (2002) in a narrow band search for gravitationally lensed Lyα emitters behind the galaxy cluster Abell 370 at $\alpha_{J2000} = 2^h39^m54\overset{s}{.}73$, $\delta_{J2000} = -1°33'32\overset{''}{.}3$. Several follow-up observations and analysis of this object have been published. In particular, from an SED analysis including constraints on its Lyα emission, Schaerer & Pelló (2005) suggested that this galaxy could show a non-negligible extinction, with $A_v \sim 1$. This re-

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⋆Based on observations carried out with the IRAM 30 meter Telescope. IRAM is supported by INSU/CNRS (France), MPG (Germany) and IGN (Spain) sult was later reinforced by the analysis of Chary et al. (2005) including also Spitzer observations, and more recently confirmed by Finlator et al. (2007). If true, the dust corrected star formation rate of HCM 6A is SFR ~ 11-41 $M_\odot$ yr^{-1}, i.e. 2 to 8 times higher than previously thought, and its luminosity is $L_{bol} \sim (1-4) \times 10^{11}$ $L_\odot$ (Schaerer & Pelló 2005) in the range of luminous infrared galaxies (LIRGs). This high SFR implies the presence of large amounts of gas, and therefore dust. This makes this strongly lensed galaxy (magnification μ=4.5 according to the model of Kneib et al. 1993) an interesting target to probe dust in very distant galaxies.

Here we report new submillimetric observations with the MAMBO-2 bolometer at the IRAM 30m telescope. These observations were conducted in the frame of a larger program dedicated to near-IR and submillimeter observations of $z > 6$ galaxies behind lensing clusters, as introduced by Schaerer et al. (2006).

The paper is structured as follows: existing and new observations of HCM 6A are described in Sect. 2. In Sect. 3 we estimate the various physical parameters, and present the overall SEDs. Our main conclusions are summarised in Sect. 4. We assume a Λ-cosmology with H_0=70 km s^{-1} Mpc^{-1}, Ω_M=0.3 and Ω_Λ=0.7.

2. Observations

In Table 1 we have compiled the available observations for HCM 6A from the literature. All fluxes have been converted to micro Jansky; 3σ limits are given for non-detections.

Table 1. Observations of HCM6A. 3σ limits are given for non-detections. Note that a nearby source, CBK4, has been detected by Cowie et al. (2002) at 850 μm. It is discussed in Sects. 2.1 and 3.1.

Filter/ instrument	wavelength [μm]	flux [μJy]	source
V	0.55	< 0.06	Hu et al. (2002)
R	0.65	0.02±0.01	
I	0.86	< 0.06	
Z	0.90	0.15±0.11	
J	1.25	0.25±0.12	
H	1.63	0.40±0.15	
K	2.12	0.16±0.13	
IRAC	3.6	0.5±0.2	Chary et al. (2006)
	4.5	1.25±0.3	
	5.8	< 2.7	
	8.0	< 3.	
JCMT	450	< 30000.	Smail et al. (2002)
	850	< 1700	Cowie et al. (2002)
MAMBO-2	1200	< 1080	this paper

2.1. Earlier observations

The optical and near-IR data (up to the K' band) is taken from the discovery paper of Hu et al. (2002).

At longer wavelength the IRAC Spitzer fluxes from Chary et al. (2006) have been used. However, due to the presence of the nearby source in the south-west already seen in images of Hu et al. (2002), the IRAC photometry may be somewhat contaminated. For this reason and given the lower spatial resolution, the MIPS 24 μm data cannot be used.

The only references mentioning observations of Abell 370 in the sub/millimeter range are Cowie et al. (2002) and Smail et al. (2002). Both refer to SCUBA (JCMT) observations and the first reference only mentions the detection of a source (source No 4 in their Table 3, hereafter CBK4) with a flux of 2.17±0.57 mJy at 850 μm and located ~ 10″ to the West of HCM 6A. This emission likely originates from a foreground galaxy of the cluster ~ 5″ to the South-West of HCM 6A. In addition this offset is larger than typical SCUBA astrometric uncertainties (~4″). However, the astrometry becomes less accurate for weaker sources and we note that for another weak source in the field the positions given by Cowie et al. (2002) and Smail et al. (2002) could differ by 10″. Indeed, the source #2 of Cowie et al. (2002) detected at 5 σ might also be detected by Smail et al. (2002) but offset by ~10″ (the source J02400-0134). Hence, it cannot be definitely excluded that the emission of CBK4 comes from HCM 6A. The galaxy would be at the border of the field covered by Smail et al. (2002) but its flux would be below their detection threshold. In short, except otherwise stated, we retain the upper limits from SCUBA in Table 1 for HCM 6A (for the 850 μm upper limit we take 3 times the uncertainty quoted for the flux of CBK4, i.e. 1.7 mJy).

2.2. New MAMBO-2 observations at 1.2 mm

The observations were carried out at the IRAM 30m Telescope with the MAMBO-2 array of 117 bolometers (Kreysa et al. 2002) during the pool session in 2004/2005. It has a half-power spectral bandwidth of 80 GHz centered on ~250 GHz (1.2 mm). The beam size is 11″, thus, any emission originating from the foreground galaxy of the cluster ~ 5″ to the South-West of HCM 6A would be dimmed by a factor of ~2. The excellent weather conditions allowed us to reach an rms of 0.36 mJy in 4.2 hours of integration in ON/OFF mode. The galaxy was not detected, the flux measured is -0.03 ± 0.36 mJy. Our non-detection corresponds to a 3σ upper limit of 1.08 mJy.

3. Results

The main derived quantities for HCM 6A are summarised in Table 2. We now discuss them one by one.

3.1. Dust mass

The upper limit on the MAMBO-2 flux allows us to compute an upper limit for the mass of dust using the fomula:

$$M_d = \frac{S_\nu/\mu\, D_L^2}{(1+z)\,\kappa_{\nu_r}\, B_{\nu_r}(T_d)} \qquad (1)$$

where S_ν is the flux upper limit, μ is the gravitational magnification factor, D_L is the luminosity distance, κ_{ν_r} is the mass

Table 2. Derived quantities for HCM 6A assuming different dust temperatures $T_{\rm d}$, a magnification μ=4.5, a dust mass absorption coefficient κ_{125}=1.875 m^2 kg^{-1}, a dust emissivity index β=1.5, and a high frequency dust spectral index α=2.9. All limits are 3σ upper limits based on the 1.2 mm flux upper limit for $T_{\rm d}$=18 and 36 K and the 850 μm flux upper limit for $T_{\rm d}$=54 K. For comparison, quantities estimated by Schaerer & Pelló (2005) are given at the bottom of the table. Note, however, that the latter SFR estimates need to be multiplied by 2.55 to account for different lower mass limits of the Salpeter IMF ($M_{\rm low}$ = 1 M$_\odot$ instead of 0.1 assumed for the SFR(IR) determination).

	$T_{\rm d}$ = 18	$T_{\rm d}$ = 36	$T_{\rm d}$ = 54
Dust mass [M$_\odot$]	$< 7.0 \times 10^8$	$< 5.3 \times 10^7$	$< 1.5 \times 10^7$
$L_{\rm FIR}$ [L$_\odot$]	$< 6.4 \times 10^{10}$	$< 2.1 \times 10^{11}$	$< 5.4 \times 10^{11}$
SFR(IR) [M$_\odot$ yr^{-1}]	< 11	< 35	< 87
$L_{\rm bol}$ [L$_\odot$]		$(1-4) \times 10^{11}$	
SFR$_{\rm UV}$(A_v = 1) [M$_\odot$ yr^{-1}]		11–41	
SFR$_{\rm Ly\alpha}$(A_v = 1) [M$_\odot$ yr^{-1}]		7–12	
SFR$_{\rm UV}$(A_v = 0) [M$_\odot$ yr^{-1}]		5.6	
SFR$_{\rm Ly\alpha}$(A_v = 0) [M$_\odot$ yr^{-1}]		0.4–0.8	

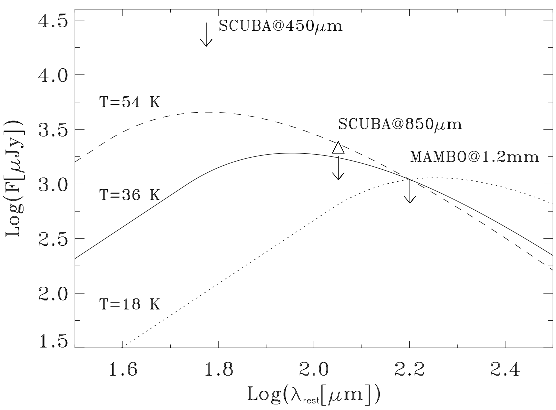

Fig. 1. Far infrared SEDs for dust temperatures of 54 K (dashed), 36 K (solid) and 18 K (dotted) with β=1.5, α=2.9 and such that $F_{\rm 1.2mm}$=1.1 mJy. The triangle shows the possible detection at 850 μm by Cowie et al. (2002), the arrows show the 3σ upper limits as summarized in Table 1.

absorption coefficient of the dust at $\nu_{\rm r}$, and $B_{\nu_{\rm r}}(T_{\rm d})$ is the intensity of a blackbody at $\nu_{\rm r}$ assuming isothermal emission from dust grains at temperature $T_{\rm d}$. To compare with the upper limits reported by Webb et al. (2007) we also assume $\kappa_{125\mu{\rm m}}$=1.875 m^2 kg^{-1} and $\kappa_\nu \propto \nu^\beta$ with the emissivity index β=1.5 and we take $T_{\rm d}$=36 K. This leads to a 3σ upper limit of $M_{\rm d}$=5.3 × 10^7 M$_\odot$. This upper limit is one order of magnitude lower than the two upper limits given by Webb et al. (2007) for two z~6.5 Lyα emitters. This significant improvement in the dust mass upper limit of a Lyα emitter at z >6 results from the high sensitivity of the observations and the strong gravitational amplification of the source.

The dust mass estimate is highly sensitive to the temperature assumed, the upper limit becomes 2.0 × 10^7 M$_\odot$ for $T_{\rm d}$=54 K and 7.0 × 10^8 M$_\odot$ for $T_{\rm d}$=18 K. In addition, the dust at high redshift is thought to result mainly from condensation of grains in SN ejecta and its emissivity might differ from that of the local Universe. With the emissivity introduced by Bianchi & Schneider (2007) for dust formed in SN ejecta we obtain 65% lower values for the upper limits on the dust mass. Uncertainties in the emissivity index must also be considered. According to Yang & Phillips (2007) the median value for LIRGs is β=1.6±0.3. Taking the higher value, i.e. β=1.9, increases the dust mass upper limits by 10%. However, despite the uncertainties, this upper limit definitely excludes the dust masses found in the high-z quasars and submillimeter galaxies (SMGs). It is closer to the mass of dust observed in local Universe galaxies (Vlahakis et al. 2005).

If the emission seen in the 850 μm map by Cowie et al. (2002) is real and if the flux effectively originates from HCM6A (cf. above discussion about CBK4), it would imply a dust mass $M_{\rm d}$=6.5 × 10^7 M$_\odot$, assuming $T_{\rm d}$ = 36 K. Taking into account the uncertainties this is compatible with our upper limit at the same temperature. Our upper limit would however imply that the dust cannot be colder than 36 K (see Fig. 1). If, as is most likely, the emission seen in their map does not originate from HCM6A, our 1.2 mm dust mass upper limit improves their 850 μm upper limit for dust colder than 36 K. For a higher dust temperature their upper limit is more stringent, e.g. at 54 K it would imply $M_{\rm d}$<1.5 × 10^7 M$_\odot$.

In the following and as summarized in Table 2 we allow for an uncertainty of 50% on the dust temperature by considering the three values, 18, 36 and 54 K. When refering to the 2 lowest temperatures we implicitly use our 1.2 mm flux upper limit and for the highest temperature we use the 850 μm upper limit from Cowie et al. (2002). The errors seem to be dominated by the uncertainty on the temperature rather than the emissivity index. In addition, if, as proposed by Yang & Phillips (2007), the emissivity index is negatively correlated to the temperature, then the variations of both parameters would compensate. To simplify the error analysis we therefore consider a range in temperature only and we assume that the resulting errors are good approximations to the errors due to all dust parameter uncertainties.

3.2. Far infrared luminosity

As Webb et al. (2007) we compute the total far infrared (FIR) luminosity assuming a modified black-body spectral energy distribution (SED) with a dust temperature of 36 K and a dust emissivity of β=1.5 and replacing the Wien's exponential decrease shortward of 53 μm by a power law with spectral index α=2.9 to better agree with observed SEDs (Blain et al. 2003). Our 1.2 mm 3σ flux upper limit corresponds to $L_{\rm FIR}$=1.9×10^{11} L$_\odot$, which is one order of magnitude lower than the FIR luminosities usually measured in the SMGs comparable to the local Universe ultraluminous infrared galaxies (Chapman et al. 2004, 2005).

This leads to an upper limit on the $L_{\rm FIR}/L_{\rm UV}$ ratio of $\sim$2. This is clearly within the range of values exhibited by Lyman-break galaxies of $L_{\rm FIR}/L_{\rm UV}$ <10 (Adelberger & Steidel 2000). Using the fits of Burgarella et al. (2005) our $L_{\rm FIR}/L_{\rm UV}$ limit translates into a dust attenuation in the far-ultraviolet (i.e. λ=1350–1750 Å) $A_{\rm FUV} \lesssim 0.9$, compatible with, but higher than the extinction estimated earlier from SED fits in the literature (Schaerer & Pelló 2005; Chary et al. 2005; Finlator et al. 2007).

The Lyα luminosity, $L_{\rm Ly\alpha} = 1.9 \times 10^{42}$ erg s^{-1}, is > 0.3% of the bolometric luminosity, which seems to follow the trend noted for Lyα blobs and SCUBA galaxies by Geach et al. (2005) and Webb et al. (2007).

3.3. Star formation rate

The upper limit on the star formation rate (SFR) derived from this FIR luminosity with the relation from Bell (2003) assuming a Salpeter IMF from 0.1 to 100 M$_\odot$ is SFR < 35 M$_\odot$ yr^{-1}. This upper limit is a factor 8–20 lower than that of Webb et al. (2007) and Carilli et al. (2007) for Lyα emitters at $z \sim 5.7$–6.6.

Although the SFR depends strongly on the dust temperature (the SFR upper limit becomes 87 M$_\odot$ yr^{-1} for $T_{\rm d}$=54 K and 11 M$_\odot$ yr^{-1} for $T_{\rm d}$=18 K as indicated in Table 2) this upper limit definitely excludes star formation rates observed in SMGs in excess of $\sim$1000 M$_\odot$ yr^{-1}. Our upper limit also excludes the high SFR suggested for HCM 6A by Chary et al. (2005), who attributed an apparent flux excess at 3.6 μm to Hα emission. The SFR limit is slightly lower but still compatible within the uncertainties with the estimates of the dust corrected SFR from Schaerer & Pelló (2005) listed also in Table 2, and based on the SED fits to UV–optical fluxes. Note that for comparison the latter SFR values should be multiplied by a factor 2.55 to account for the different lower mass limit of the IMF ($M_{\rm low}$ = 1 M$_\odot$).

3.4. Star formation rate density

The gravitational magnification allows us to probe a galaxy with a lower Lyα luminosity, i.e. $L_{\rm Ly\alpha}$=2 $\times$ 10^{42} erg s^{-1} instead of 7.5 $\times$ 10^{42} erg s^{-1} for the average of the 2 galaxies discussed by Webb et al. (2007). According to the luminosity function (LF) of Kashikawa et al. (2006) the cumulative number density is at least 10 times higher at this luminosity and our upper limit on the SFR should therefore be more representative for the whole population of Lyα emitters.

To determine an upper limit for the infrared-measured SFR density (SFRD) we assume that the number density is given by the cumulative number density at $L_{\rm Ly\alpha}$=2 $\times$ 10^{42} erg s^{-1}, which is $N(> L) \sim 7. \times 10^{-4}$ Mpc^{-3}. For $T_{\rm d}$ = 36 K, we then obtain SFRD(IR)< 2.4 $\times$ 10^{-2} M$_\odot$ yr^{-1} Mpc^{-3}, with a possible uncertainty of a factor of $\sim$ 3 due to the unknown dust temperature (cf. Table 2). Integration over the LF of Kashikawa et al. (2006) down to 0.5$L_\star$ (assuming $\alpha = -1.5$, $\log L_\star = 42.6$, and that $L_{\rm Ly\alpha}$ has the same proportionality with SFR at all luminosities) would imply an SFRD higher by a factor 2.2.

Incidentally our upper limit for SFRD(IR) is very similar to the value estimated by Webb et al. (2007). However, we note that these authors adopted a lower value for the cumulative number density drawn from the spectroscopically confirmed sample of Kashikawa et al. (2006), whereas we use the LF from the complete z = 6.5 sample. The SFRD(IR) limit can be regarded as a first estimate of the dust-obscured SFR density of Lyα selected galaxies at $z \sim 6.6$. More observations are clearly needed to improve this estimate.

For comparison, integration of the complete Lyα LF, with the same assumptions as above, yields SFRD(Lyα)=2.7 $\times$ 10^{-3} M$_\odot$ yr^{-1} Mpc^{-3} at z = 6.6 assuming a standard Lyα SFR conversion of SFR(Lyα)= 9.1 $\times$ 10^{-43}$L_{\rm Ly\alpha}$ erg s^{-1}. For well known reasons (dust and radiation transfer effects, partial IGM transmission) this should represent a lower limit of the SFRD of Lyα emitters at this redshift.

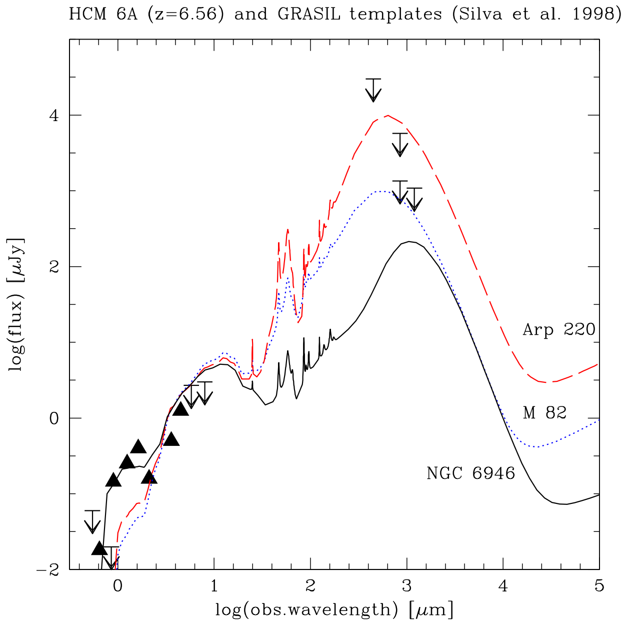

Fig. 2. Comparison of the observed SED of HCM 6A (the data points are listed in Table 1) with GRASIL templates for Arp 220, M82, and NGC 6946 from Silva et al. (1998) (from top to bottom in the IR, normalised arbitrarily at 4 μm). The observations in the near-IR and/or sub/millimeter range rule out Arp 220 and M82 like templates, but are compatible with normal galaxies as NGC 6946.

3.5. Comparison to empirical SEDs

In Fig. 2 we compare the observed SED (cf. Table 1) with semi-empirical templates from the GRASIL models of Silva et al. (1998). Shown are the templated of Arp220, a prototypical ULIRG, the prototypical starburst galaxy M82, and NGC 6946, an Scd galaxy. Figure 3 shows a comparison with the observed SEDs of low metallicity blue compact dwarf galaxies from Hunt et al. (2005). Clearly the observed millimeter to IR flux ratio excludes the ULIRG SED, and possibly also the dusty starburst (M82). This is in agreement with the moderate extinction ($A_V \lesssim 1$) estimated from the fits to the (restframe) UV–optical observations. On the other hand, the SED of HCM 6A is compatible with that of normal galaxies, like NGC 6946, and with the SEDs of blue compact dwarf galaxies (BCD). The

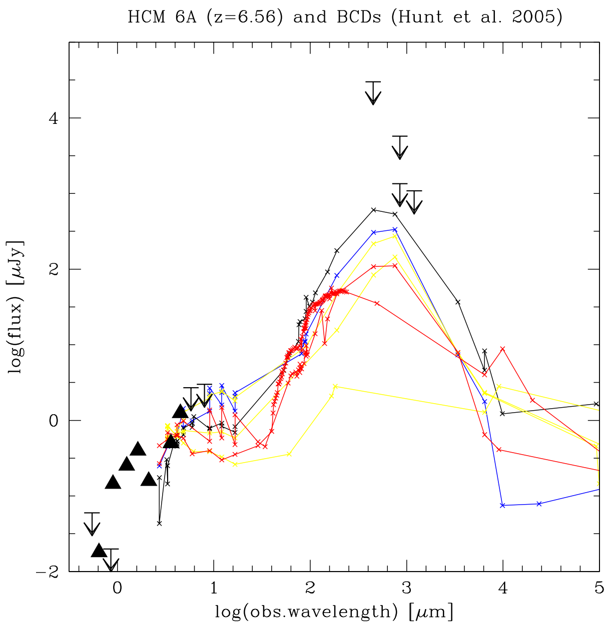

Fig. 3. Comparison of the observed SED of HCM 6A with templates of low metallicity Blue Compact Dwarf galaxies from Hunt et al. (2005) normalised arbitrarily at 4 μm. The SED of BCDs, including the rest-frame UV part not shown here, are compatible with HCM 6A.

present data does not allow us to distinguish between these two different types of SEDs, which mostly differ in their average dust temperature (dust being hotter in BCDs). However, HCM 6A resembles more likely BCDs with higher surface brightness (or SFR surface density) than spiral galaxies. This is also found more generally for high-z Lyα emitters (Dow-Hygelund et al. 2007). In fact, local BCDs have SFR ~0.2–3 $M_\odot$ yr^{-1}, quite similar to the lower limit determined for HCM 6A.

From the empirical SEDs shown in Figs. 1 and 2 we see that the millimeter flux may be close to a detection. In any case this object will be an interesting target for ALMA, which should be able to characterise the dust properties of this faint distant galaxy.

4. Discussion and conclusions

Quantifying the dust content in distant galaxies is important to constrain dust formation mechanisms in the early Universe and to determine cosmological properties such as the star formation rate density (SFRD) at high redshift. Strong gravitational lensing provides a unique access to the faintest observable sources probing the galaxy luminosity function down to more representative objects. Here we have used this effect to measure the millimeter emission of a faint lensed Lyα emitter, suspected to suffer from a non-negligible amount of extinction in earlier studies.

Our MAMBO-2 observations of the $z = 6.56$ galaxy HCM 6A yield an upper limit of 1.08 mJy (3σ) at 1.2 mm. For typical dust parameters, this translates into upper limits of $\lesssim 5\times10^7$ $M_\odot$ for the dust mass, $\lesssim 2\times10^{11}$ $L_\odot$ for the infrared luminosity, and $\lesssim 35$ $M_\odot$ yr^{-1} for the IR star formation rate (SFR). Thanks to strong gravitational lensing and to excellent weather conditions these limits improve recent sub-mm measurements of two $z \sim 6.5$ Lyα emitters by approximately one order of magnitude.

Assuming a dust production of ~ 0.1 $M_\odot$ per type II supernova (Bianchi & Schneider 2007) a maximum age of $\sim 1/2t_H \approx 4\times10^8$ yr, would require a constant SFR ~ 60 $M_\odot$ yr^{-1} (for $M_{\rm low} = 1$ $M_\odot$) to produce 5×10^7 $M_\odot$ of dust. Hence our results are marginally consistent with current estimates for the dust production. Reducing the large age uncertainty of HCM 6A, and lowering the upper limit for its dust mass will allow to place more severe constraints on dust formation scenarios.

Our non-detection of dust does not exclude the presence of dust in HCM 6A. In fact the SFR(IR) upper limit of $\lesssim 35$ $M_\odot$ yr^{-1}, with a typical uncertainty of a factor 3 in either direction, comes close to but remains compatible with the UV SFR of $\sim$ 28–105 $M_\odot$ yr^{-1} obtained by Schaerer & Pelló (2005)[1] for an extinction of $A_V \sim 1$. Its is tempting then to speculate that the IR emission from this object could soon be detected with somewhat deeper sub/millimeter observations. However, another explanation for the apparently red SED of the Lyα emitter HCM6A may also be a composite stellar population with little or no dust, as discussed by Schaerer & Pelló (2005). Deeper sub/millimeter observations of lensed high-z galaxies including HCM6A should therefore soon be able to match the constraints from shorter wavelength observations and provide more detailed constraints on dust in the early Universe.

Thanks to gravitational lensing the Lyα emitter observed here corresponds, with $L_{\rm Ly\alpha} = 1.9\times10^{42}$ erg s^{-1}, to a $\sim 0.5L_\star$ galaxy according to the $z \sim 6.5$ Lyα luminosity function (LF) of Kashikawa et al. (2006), at the faintest limits of their blank field survey limits. Using our millimeter non-detection and their LF we determine an upper limit for the infrared-measured SFRD of $< 2.4\times10^{-2}$ $M_\odot$ yr^{-1} Mpc^{-3} with an uncertainty of a factor 3 in either direction. This can be regarded as an estimate of the dust-obscured SFR density of Lyα selected galaxies at $z \sim 6.6$. More observations will be needed to improve this estimate. Gravitational lensing and new upcoming facilities should allow significant progress in the near future.

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References

Adelberger, K. L. & Steidel, C. C. 2000, ApJ, 544, 218
Bell, E. F. 2003, ApJ, 586, 794
Bertoldi, F., Carilli, C. L., Cox, P., et al. 2003a, A&A, 406, L55
Bertoldi, F., Cox, P., Neri, R., et al. 2003b, A&A, 409, L47
Bianchi, S. & Schneider, R. 2007, MNRAS, 378, 973

[1] The SFR(UV) value quoted here has been converted to the same "standard" IMF adopted for the SFR(IR); cf. Sect. 3.3

Blain, A. W., Barnard, V. E., & Chapman, S. C. 2003, MNRAS, 338, 733
Burgarella, D., Buat, V., & Iglesias-Páramo, J. 2005, MNRAS, 360, 1413
Carilli, C. L., Murayama, T., Wang, R., et al. 2007, ApJS, 172, 518
Chapman, S. C., Blain, A. W., Smail, I., & Ivison, R. J. 2005, ApJ, 622, 772
Chapman, S. C., Smail, I., Blain, A. W., & Ivison, R. J. 2004, ApJ, 614, 671
Chary, R.-R., Stern, D., & Eisenhardt, P. 2005, ApJ, 635, L5
Cowie, L. L., Barger, A. J., & Kneib, J.-P. 2002, AJ, 123, 2197
Dow-Hygelund, C. C., Holden, B. P., Bouwens, R. J., et al. 2007, ApJ, 660, 47
Fan, X. 2006, New Astronomy Review, 50, 665
Finlator, K., Davé, R., & Oppenheimer, B. D. 2007, MNRAS, 376, 1861
Geach, J. E., Matsuda, Y., Smail, I., et al. 2005, MNRAS, 363, 1398
Hu, E. M., Cowie, L. L., McMahon, R. G., et al. 2002, ApJ, 568, L75
Hunt, L., Bianchi, S., & Maiolino, R. 2005, A&A, 434, 849
Kashikawa, N., Shimasaku, K., Malkan, M. A., et al. 2006, ApJ, 648, 7
Kneib, J. P., Mellier, Y., Fort, B., & Mathez, G. 1993, A&A, 273, 367
Kreysa, E., Gemünd, H.-P., Raccanelli, A., Reichertz, L. A., & Siringo, G. 2002, in American Institute of Physics Conference Series, Vol. 616, Experimental Cosmology at Millimetre Wavelengths, ed. M. de Petris & M. Gervasi, 262–269
Loeb, A. & Barkana, R. 2001, ARA&A, 39, 19
Page, L., Hinshaw, G., Komatsu, E., et al. 2006, ArXiv Astrophysics e-prints, astro-ph/0603450
Priddey, R. S., Isaak, K. G., McMahon, R. G., Robson, E. I., & Pearson, C. P. 2003, MNRAS, 344, L74
Robson, I., Priddey, R. S., Isaak, K. G., & McMahon, R. G. 2004, MNRAS, 351, L29
Schaerer, D. & Pelló, R. 2005, MNRAS, 362, 1054
Schaerer, D., Pelló, R., Richard, J., et al. 2006, The Messenger, 125, 20
Schneider, R., Ferrara, A., & Salvaterra, R. 2004, MNRAS, 351, 1379
Silva, L., Granato, G. L., Bressan, A., & Danese, L. 1998, ApJ, 509, 103
Smail, I., Ivison, R. J., Blain, A. W., & Kneib, J.-P. 2002, MNRAS, 331, 495
Todini, P. & Ferrara, A. 2001, MNRAS, 325, 726
Venkatesan, A., Schneider, R., & Ferrara, A. 2004, MNRAS, 349, L43
Vlahakis, C., Dunne, L., & Eales, S. 2005, MNRAS, 364, 1253
Walter, F., Bertoldi, F., Carilli, C., et al. 2003, Nature, 424, 406
Wang, R., Carilli, C., Beelen, A., et al. 2007, ArXiv e-prints, astroph/0704.2053
Webb, T. M. A., Tran, K.-V. H., Lilly, S. J., & van der Werf, P. 2007, ApJ, 659, 76
Willott, C. J., Delorme, P., Omont, A., et al. 2007, ArXiv e-prints, astroph/0706.0914
Yang, M. & Phillips, T. 2007, ApJ, 662, 284