An extended Herschel drop-out source in the center of AS1063: a ‘normal’ dusty galaxy at $z = 6.1$ or SZ substructures?

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In the course of our 870μm APEX/LABOCA follow up of the Herschel Lensing Survey we have detected a source in AS1063 (RXC J2248.7-4431), that has no counterparts in any of the Herschel PACS/SPIRE bands, it is a Herschel ‘drop-out’ with $S_{870}/S_{500} \geq 0.5$. The 870μm emission is extended and centered on the brightest cluster galaxy suggesting either a multiply imaged background source or substructure in the Sunyaev-Zel’dovich (SZ) increment due to inhomogeneities in the hot cluster gas of this merging cluster. We find that this source could be the first SMG with a moderate far infrared luminosity ($L_{FIR} \sim 10^{12} L_{\odot}$) detected so far at $z > 4$. In deep HST observations we identified a multiply imaged $z \sim 6$ source and we measured its spectroscopic redshift $z = 6.107$ with VLT/FORS. This source could be associated with the putative SMG but it is most likely offset spatially by 10-30 kpc and they could be interacting galaxies. With a FIR luminosity in the range $[5 - 15] \times 10^{11} L_{\odot}$ corresponding to a star formation rate in the range $[80 - 260] M_{\odot} yr^{-1}$, this SMG would be more representative than the extreme starbursts usually detected at $z > 4$. With a total magnification of $\sim 25$ it would open a unique window to the ‘normal’ dusty galaxies at the end of the epoch of reionization.

Key words. galaxies:high-redshift, submillimeter: galaxies, galaxies: evolution

1. Introduction

Estimating the contribution of dust obscured star formation in the early Universe is essential to constrain the models of galaxy evolution and it has been a growing field of research since the late 1990s (e.g., Blain et al. 2002). Submillimeter (submm) surveys have proven to be very efficient at detecting distant dusty galaxies (also known as Submillimeter Galaxies, SMGs) owing to the negative K-correction and their redshift distribution was found to peak at $z \sim 2 - 3$ (Chapman et al. 2005).

With the advent of a new generation of submm instruments the hunt for the highest redshift SMGs progressed at a rapid pace in recent years. The first SMG beyond $z = 5$ was discovered by Capak et al. (2011) with JCMT/AzTEC. Based on a Herschel detection and a 30m/EMIR follow up, Combes et al. (2012) discovered an interacting system of bright SMGs at $z = 5.243$. At the same time Walter et al. (2012) using IRAM instruments found that an SMG known for years in the Hubble deep field is actually a system of galaxies lying at $z = 5.2$. Following up on SPT bolometer observations Vieira et al. (2013), and Weiß et al. (2013) measured with ALMA the spectroscopic redshifts of 23 new SMGs out of which two are at $z > 5$. In parallel, Riechers et al. (2013) observed ‘red’ SMGs based on Herschel colors with CARMA and discovered the highest redshift SMG at $z = 6.34$. 

LETTER TO THE EDITOR
In terms of luminosity, however, all the SMGs detected so far beyond $z > 4$ are ultraluminous infrared galaxies (ULIRGs) with $L_{\text{IR}} > 10^{12} L_{\odot}$ or even hyperluminous infrared galaxies (HyLIRGs) with $L_{\text{IR}} > 10^{13} L_{\odot}$, implying star formation rates $\geq 10^3 M_{\odot} \text{yr}^{-1}$. As confirmed by recent ALMA number counts (Koskinen et al. 2013; Hatsukade et al. 2013) these extreme starbursts are not representative of the average population of dusty star forming galaxies at $z > 4$ and the luminous infrared galaxies (LIRGs) with $L_{\text{IR}} \sim 10^{10} L_{\odot}$ that should represent the majority remain to be discovered. The lensing power provided by massive galaxy clusters is widely used to detect distant galaxies (e.g., Smail et al. 1997). However, the recent discovery of substructures in the Sunyaev-Zel’dovich (SZ) increment of interacting clusters (Kornegut et al. 2011; Mróz et al. 2012) may complicate the interpretation of submm observations. We report here the discovery of a good candidate for a normal star forming galaxy at $z \approx 6.1$ lensed by the cluster AS1063 (RXCJ2248.7-4431) and we discuss the possibility that this source could instead correspond to substructures in the SZ effect. We adopt the $\Lambda$CDM concordance cosmology: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\Lambda} = 0.73$.

### 2. Observations and data reduction

**Herschel** observations of AS1063 at 70, 100, 160, 250, 350 and 500 $\mu$m were obtained as part of the *Herschel* Lensing Survey (program IDs: KPOT_eegami_1, OT2_trawle_3) as described by Egami et al. (2010) and Rawle et al. (2010). The full width at half maximum (FWHM) of the beams are 5.2″, 7.7″, 11.3″, 18.1″, 24.9 and 36.6″, respectively.

Observations of AS1063 at 870 $\mu$m with the Large APEX Bolometer Camera LABOCA (Siringo et al. 2009) were obtained in the frame of the LABOCA Lensing Survey, a large program coordinated between ESO and MPI (E187A0437A, M-087,F-0005-2011). The observations were carried out in April and May 2012 in excellent weather conditions with an average precipitable water vapor (PWV) of 0.5 mm. The spiral mapping pattern was chosen to cover a circular area of $\sim 8'$ in diameter centered on the clusters. Absolute flux calibration was achieved through observations of Mars, Uranus and Neptune as well as secondary calibrators and was found to be accurate within $\pm 10\%$ (rms). The atmospheric attenuation was determined via skypoints every $2$ hours as well as from independent data from the APEX radiometer which measures the line of sight water vapor column every minute (see Siringo et al. 2009 for a more detailed description). Pointing was checked on the nearby quasars and found to be stable within 3″ (rms). The data were reduced using the Bolometer array data Analysis software (BoA, Schuller et al. in prep.). The effective resolution of the maps is 24.3″. The pixel noise RMS at the center of the map is 1.1 mJy beam$^{-1}$.

### 3. Results

The LABOCA map shows a source at the center of the cluster AS1063 (Fig. 1) that is extended at the resolution of LABOCA

$\lambda_l$ | 24 | 70 | 100 | 160 | 250 | 350 | 500 | 870  
--- | --- | --- | --- | --- | --- | --- | --- | ---  
$S_\nu$ | <0.06 | <0.75 | <1.2 | <3.8 | <7.2 | <9.9 | <12.3 | 7.6±1.1  

In terms of luminosity, however, all the SMGs detected so far beyond $z > 4$ are ultraluminous infrared galaxies (ULIRGs) with $L_{\text{IR}} > 10^{12} L_{\odot}$ or even hyperluminous infrared galaxies (HyLIRGs) with $L_{\text{IR}} > 10^{13} L_{\odot}$, implying star formation rates $\geq 10^3 M_{\odot} \text{yr}^{-1}$. As confirmed by recent ALMA number counts (Koskinen et al. 2013; Hatsukade et al. 2013) these extreme starbursts are not representative of the average population of dusty star forming galaxies at $z > 4$ and the luminous infrared galaxies (LIRGs) with $L_{\text{IR}} \sim 10^{10} L_{\odot}$ that should represent the majority remain to be discovered. The lensing power provided by massive galaxy clusters is widely used to detect distant galaxies (e.g., Smail et al. 1997). However, the recent discovery of substructures in the Sunyaev-Zel’dovich (SZ) increment of interacting clusters (Kornegut et al. 2011; Mróz et al. 2012) may complicate the interpretation of submm observations. We report here the discovery of a good candidate for a normal star forming galaxy at $z \approx 6.1$ lensed by the cluster AS1063 (RXCJ2248.7-4431) and we discuss the possibility that this source could instead correspond to substructures in the SZ effect. We adopt the $\Lambda$CDM concordance cosmology: $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\Lambda} = 0.73$.

### 4. Discussion

#### 4.1. Photometry of a putative lensed source

In a second iteration we run the photometry procedure again to fit simultaneously two sources at the positions of the 870 $\mu$m peaks in addition to the two low-$z$ sources. We assume that the two 870 $\mu$m sources are the images of a single lensed source, which implies a unique peak wavelength (same redshift and dust temperature) and a total of 7 free parameters. The $\chi^2$ value gives us an indication of the quality of the fit, it is plotted against the redshift and the dust temperature of the lensed source in the Fig. 2 with contours indicating the confidence levels. At a given dust temperature, the 870 $\mu$m flux and the *Herschel* upper limits impose a lower limit to the redshift. Thus, if we assume $T_d > 20 \text{ K}$ as observed in most SMGs including the lowest luminosities (see, e.g., Symeonidis et al. 2013; Magnelli et al. 2012 or Swinbank et al. submitted), then the source must be at $z \geq 2$. If $T_d = 30 \text{ K}$ (mean value for $L_{\text{IR}} \sim 10^{11.5} L_{\odot}$ according to the same references), then the redshift must be $\geq 4$. In addition, if we assume $z < 7$, the observed (i.e., uncorrected for lensing) FIR luminosities of the two peaks must be $< 10^{13} L_{\odot}$ (Fig. 3).

#### 4.2. Lens and source models

Based on the identification of 13 multiple image systems out of which 5 have a spectroscopic redshift and the others have a reliable photometric redshift, we have built a lens model of the cluster (Richard et al. in prep). The critical lines computed with this model for $z=6$ are shown in the Fig. 2 in red. As shown on the left panel of Fig. 2 with this model we can reproduce the two 870 $\mu$m peaks by assuming a single source modeled by a circular Gaussian of FWHM=2’kpc at $z = 6$. Four images of the source, labeled L1, L2, L3 and L4, are actually formed in a classical quad configuration; their magnifications are $10.8$, $3.7$, $7.1$ and $3.1$, respectively for a total magnification $\mu=25.5$. The images L3 and L4 are $\sim 3\times$ fainter than L1 and are therefore at $\sim 2\sigma$, which is consistent with no detection. To ob-

\footnote{The lowest luminosity SMG detected so far at $z > 4$ has $L_{\text{IR}} = 1.3 \times 10^{12} L_{\odot}$ and is at $z = 4.04$ (Knudsen et al. 2010).}
A plausible HST counterpart at \( z = 6.107 \)

In the HST images and catalogs provided by the CLASH project we identified 4 objects (named 6.1, 6.2, 6.3 and 6.4 in Fig. 2) as in Richard et al. in prep.), which could be the 4 images of a high-z source. Indeed, fitting various SED templates to the HST photometry we derived a redshift \( z = 6.3 \pm 0.3 \) (Fig. 2) and the image positions were accurately reproduced by our lens model for a source at \( z \sim 6 \). To confirm the redshift we recently obtained VLT/FORS spectroscopy of the 6.2, 6.3 and 6.4 images. The Ly-\( \alpha \) line is clearly detected at \( z = 6.107 \) (Fig. 3). The magnifications are \( \mu_{6.1}=17.1, \mu_{6.2}=6.7, \mu_{6.3}=5.9 \) and \( \mu_{6.4}=2.5 \).

The image 6.1 of this HST source benefits from a boost by the same two galaxies of the cluster as in the model discussed above for the 870\( \mu \)m emission. However, if they are both at the same redshift the LABOCA source needs to be offset from the HST source to reproduce the southern peak (L2); it is at \( \sim 30 \) kpc in the above model. The distance between the two sources is mainly constrained by the flux ratio of the two 870\( \mu \)m peaks, it could be in the range 10-30 kpc, suggesting interacting galaxies.

The star formation rate (SFR) of the HST source estimated from the UV continuum and from the Ly-\( \alpha \) line and corrected for lensing are SFR\(_{UV} \sim 5 \times 10^{-11} \) L\(_{\odot} \) yr\(^{-1}\) and SFR\(_{\alpha} \sim 15 \times 10^{-11} \) L\(_{\odot} \) yr\(^{-1}\). The Spitzer detection of 6.3 at 3.6\( \mu \)m implies (H-3.6) = 2, redder than for typical \( z \sim 6-8 \) LBGs (McLure et al. 2011). SED fits with

In a recent paper Bradley et al. (2013) mention a quintuple system in this cluster but they list only 3 of our identified images (6.1, 6.3 and 6.4). After the submission of our letter two other articles appeared online (Monna et al. 2013; Balestra et al. 2013) describing in more detail this system and providing a similar spectroscopic redshift. We confirm the fifth image identified by these authors and show it in the Fig. 2 as "6.5".
Fig. 2. Left: Residuals of the 870µm emission after subtraction of the two low-z sources. The cyan contours represent the $z = 6$ source model lensed by the cluster and observed at the resolution of LABOCA. The four images formed are labeled L1, L2, L3 and L4. The contour levels are at 0.25, 0.5 and 0.75×$S_{L1}$, where $S_{L1}$ is the peak flux of the L1 image. The critical lines for $z = 6$ are overlaid in red. Right: HST color image of the center of the cluster AS1063 made from images in the filters F606W (blue), F775W (green) and F125W (red). The white squares show the positions of the 4 images of a $z = 6.1$ background source. The green contours show the 870µm emission at 2.6, 3.9, 5.2 and 6.5 mJy (RMS=1.1 mJy). The dotted green circle represents the LABOCA beam (FWHM=24.3″).

Fig. 3. Left panel: $\chi^2$ map in the $z$-$T_d$ plane, where $z$ and $T_d$ are the redshift and the dust temperature assumed for the 870µm source detected with LABOCA. The two 870µm-peaks shown in the Fig. 2 as well as the two low-z sources (at $z = 0.6$ and 0.3) shown in the Fig. 1 are fitted simultaneously at all wavelengths from 100 to 870µm assuming a modified black body SED for each source (7 free parameters). The white contours show the 1σ, 2σ, 3σ, 4σ confidence levels. Middle and right panels: the best fit FIR luminosity in log and without any lensing correction in the $z$-$T_d$ plane for the two 870µm peaks. The white contours are spaced by 0.5 dex. The $\chi^2$ 3σ confidence level is over-plotted in red.

young populations predict up to $A_v \sim 1.5$ implying a reprocessed IR luminosity of $\sim 4 \times 10^{11} L_\odot$, i.e., an SFR$_{IR} \sim 70 M_\odot$ yr$^{-1}$.

At $z = 6.1$ the upper limit on the FIR luminosity of the 870µm source depends on the SED template assumed as illustrated on the right panel of Fig. 3. The intrinsic luminosities obtained are in the range $[5-15] \times 10^{11} L_\odot$, which corresponds to an SFR in the range $[80-260] M_\odot$ yr$^{-1}$. The star forming properties of the HST and the LABOCA sources could therefore be similar.

4.4. SZ substructure in the merging cluster?

AS1063 is known to yield a strong SZ effect (Plagge et al. 2010) that was detected at S/N$\sim$17 with Planck (Planck Collaboration et al. 2013). Furthermore, Gómez et al. (2012) showed that this cluster is undergoing a major merging event close to the plane of the sky and there has been growing evidences in recent years, both from observations and simulations, that such a merging configuration can produce small scale substructures in the SZ (Korngut et al. 2011; Mroczkowski et al. 2012; Ruan et al. 2013). These substructures could be caused by shocks and inhomogeneities in the hot gas and their increment could
Fig. 4. Left: SED fits to the HST/ACS-WFPC3 photometry of the images B and D (A is contaminated by a nearby source, C is in a noisy strip of the detector). The best fits give $z = 6.3 \pm 0.3$. The inset shows the VLT/FORS spectrum of the B image with the Ly-$\alpha$ line clearly detected at $z = 6.107$ (Richard et al in prep). The x-axis of the inset corresponds to the observed wavelength in Å. Right: SED fits to the 870μm northern peak taking into account the upper limits listed in the Table 1 and assuming $z = 6.1$ and $\mu = 10$ (all the fluxes are corrected for magnification). The modified black body SED with $T = 30$ K is shown in blue, it gives a FIR luminosity $L_{\text{FIR}} \approx 5 \times 10^{11} L_\odot$. The other templates come from the Vega et al. (2008) library (green), the Michałowski et al. (2010a, b) library (cyan) and the Polletta et al. (2007) library (orange). The template in magenta corresponds to the SMM J2135-0102 model (Swinbank et al. 2010; Ivison et al. 2010).

Fig. 5. Chandra X-ray map of AS1063 overlaid with the LABOCA residuals in green contours starting at $2\sigma$ and spaced by $1\sigma$. The blue circles mark the positions the two components of the $\beta$-model fitted by Gómez et al. (2012) to the Chandra data. The northern LABOCA peak is close to the secondary mass component identified by Gómez et al. (2012) (Fig. 5) and its elongated morphology will be consistent with shocked gas. The large scale SZ would be filtered out by the LABOCA observations and the data reduction, and we would be seeing the substructures related to the merging event. More quantitatively, the Planck measurement at 353 GHz (the central pixel is at 0.12 MJy/sr) can be used to scale the SZ profile modeled by Plagge et al. (2010) for this cluster and thus estimate the peak flux expected at the center of the LABOCA map ignoring spatial filtering. We obtain $\sim 7$ MJy/beam. The fraction of this flux filtered by the observations is difficult to estimate from the data because it depends on the morphology of the SZ increment. This will be studied in a forthcoming paper by Zemcov et al. (in prep).

5. Conclusion

With APEX/LABOCA we have detected an extended 870μm source associated with the center of the cluster AS1063. The source is not detected at shorter FIR/submm wavelengths. We find two possible interpretations of this peculiar source, it could be the dusty component of an HST-detected strongly-lensed galaxy at $z=6.1$ or substructures in the SZ effect. The current observations do not allow us to disentangle the two interpretations.

There are two routes to decide between the different origins of the features we have discovered: submm observations with ALMA should allow us to resolve the four images of the high-$z$ source, while lower frequency observations (150 GHz) are required to measure the decrement of the SZ substructures.

Acknowledgements. We are very grateful to the APEX staff for their great help with the observations and their nice welcome at the Sequitor base. We gratefully acknowledge the ESO director for the VLT/FORS program DDT 291.A-5027. We kindly acknowledge Etienne Pointecouteau for providing us with the Planck data and for useful discussions. This work received support from the Agence Nationale de la Recherche bearing the reference ANR-09-BLAN-0234. JPK thanks support from the European Research Council (ERC) advanced grant Light on the Dark (LIDA) and CNRS. IRS acknowledges support from STFC (ST/K001573/1), a Leverhulme Fellowship, the ERC Advanced Investigator programme DUSTYGAL 321334 and a Royal Society/Wolfson Merit Award. AMS acknowledges an STFC Advanced Fellowship through grant ST/H005234/1. KK thanks the Swedish Research Council for support (grant 621-2011-5372).

References


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