Early science with the Large Millimeter Telescope: dust constraints in a $z \sim 9.6$ galaxy

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ABSTRACT
Recent observations with the Gismo (Goddard-IRAM Superconducting 2 Millimeter Observer) 2 mm camera revealed a detection 8 arcsec away from the lensed galaxy MACS 1149-JD1 at $z = 9.6$. Within the 17.5 arcsec FWHM Gismo beam, this detection is consistent with the position of the high-redshift galaxy and therefore, if confirmed, this object could be claimed to be the youngest galaxy producing significant quantities of dust. We present higher resolution (8.5 arcsec) observations of this system taken with the AzTEC 1.1 mm camera mounted on the Large Millimeter Telescope Alfonso Serrano. Dust continuum emission at the position of MACS 1149-JD1 is not detected with an r.m.s. of 0.17 mJy/beam. However, we find a detection $\sim 11$ arcsec away from MACS 1149-JD1, still within the Gismo beam which is consistent with an association to the Gismo source. Combining the AzTEC and Gismo photometry, together with Herschel ancillary data, we derive a $z_{\text{phot}} = 0.7$–1.6 for the dusty galaxy. We conclude therefore that the Gismo and AzTEC detections are not associated with MACS 1149-JD1. From the non-detection of MACS 1149-JD1 we derive the following $(3\sigma)$ upper limits corrected for gravitational lensing magnification and for cosmic microwave background effects: dust mass $< 1.6 \times 10^7 \, M_\odot$, IR luminosity $< 8 \times 10^{10} \, L_\odot$, star formation rate $< 1.4 \, M_\odot \, \text{yr}^{-1}$, and UV attenuation $< 2.7$ mag. These limits are comparable to those derived for other high-redshift galaxies from deep Atacama Large Millimeter/submillimeter Array observations.

Key words: dust, extinction–galaxies: high redshift–galaxies: ISM–submillimetre: galaxies.

1 INTRODUCTION
Dust is an extremely important ingredient of the Universe and plays an essential role in the formation and growth of different astronomical objects, from planets to the most massive galaxies. Dust obscures ultraviolet (UV) and optical emission from young stars in regions of intense star formation and re-emits it into far-infrared (FIR) bands, affecting the observed spectral properties (e.g. Draine 2003). Understanding the properties of dust in the very young universe is of great importance, since its abundance and composition provide critical information about the interstellar medium conditions at the epoch of reionization, as well as about the number and total energy output of stellar sources which likely contributed to the process of reionization. Furthermore, observations at these early epochs, when dust was being formed for the first time, have important consequences on our understanding of dust formation processes and the chemical enrichment of the Universe (e.g. Dwek, Galliano & Jones 2007; Michałowski et al. 2010b; Calura et al. 2014; Valiante et al. 2014; Mancini et al. 2015; Michałowski 2015).

Dust has been detected in the $z = 6.3$ submm galaxy HLFS3 (Riechers et al. 2013), the quasars SDSS J1148+5251 at $z = 6.42$ (Fan et al. 2003) and ULAS J1120+0641 at $z = 7.1$ (Venemans et al. 2012), and the $z = 7.5$ ‘normal’ star-forming galaxy AL 1689-zD1 (Watson et al. 2015). On the other hand, recent interferometric studies report non-detections of dust in $z \sim 6$–8 galaxies (Walter et al. 2012; Ouchi et al. 2013; Berger et al. 2014; González-López et al. 2014; Ota et al. 2014; Schaefer et al. 2015), leading to the belief that most normal galaxies at these high redshifts may be largely dust-free due to their presumed low metallicities. This is supported

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by the demonstration of a very low mass dust reservoir in I Zw18, a metal-poor local galaxy (Fisher et al. 2014; Hunt et al. 2014). Clearly, the presence and abundance of dust in the high-redshift Universe is still poorly understood and, therefore, observations of dust of larger samples of galaxies at high redshifts are necessary.

MACS1149-JD1 is believed to be a gravitationally lensed galaxy, which is strongly magnified ($\mu = 14.5^{+1.7}_{-1.0}$, Zheng et al. 2012) by the Frontier Field (FF) galaxy cluster MACS J1149.6+2223 at $z = 0.544$ (Ebeling et al. 2007). The Hubble Space Telescope (HST) and Spitzer colours indicate that MACS1149-JD1 is a young galaxy with a photometric redshift of $z_{\text{phot}} = 9.6 \pm 0.2$ (Zheng et al. 2012). The large number of bands used to derive the photometric redshift makes it one of the most accurate estimates obtained for such a distant object. Recently, Dwek et al. (2014) have reported a potential 2 mm detection of MACS1149-JD1, using the Goddard-IRAM Superconducting 2 Millimeter Observer (GISMO) camera (Staguhn et al. 2008) mounted at the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope, with a 17.5 arcsec full width at half-maximum (FWHM) beam size, but with an effective 24.7 arcsec FWHM smoothed-beam for point-source extraction. The 99 per cent confidence interval for the positional uncertainty of this source is $\sim 11$ arcsec, following the description by Ivison et al. (2007), consistent with the offset from the high-redshift galaxy ($\sim 8$ arcsec). Furthermore, the 2 mm number counts (Staguhn et al. 2014) predicts a probability of 0.3–0.8 per cent to find such a source at random, which suggests that the GISMO detection might be associated with the high-redshift galaxy.

In this Letter, we present 8.5 arcsec FWHM resolution observations taken during the Early Science Phase of the Large Millimeter Telescope Alfonso Serrano (LMT; Hughes et al. 2010) using the 1.1 mm continuum camera AzTEC (Wilson et al. 2008) in order to confirm or rule out the association of the mm-wavelength source with MACS1149-JD1, as well as constrain the dust properties of this system.

All our calculations assume a $\Lambda$ cold dark matter cosmology with $\Omega_m = 0.68$, $\Omega_{\Lambda} = 0.32$, and $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration XVI 2013).

2 OBSERVATIONS

2.1 AzTEC/LMT observations

Our observations were obtained using the 1.1 mm continuum camera AzTEC on the LMT. During this Early Science Phase (see also Zavala et al. 2015), only the inner 32 m diameter section of the LMT primary surface is illuminated, leading to an effective beam size of $\theta_{\text{FWHM}} = 8.5$ arcsec, a factor of $\sim 3$ better than the smoothed-GISCO/IRAM beam.

The observations were conducted in photometry mode over several observing nights between 2014 December and 2015 April with opacities in the range of $T_{255 \text{ GHz}} = 0.03$–0.12. The scanning technique used was a Lissajous pattern covering a 1.5 arcmin diameter region with uniform noise centred at the HST position of MACS1149-JD1. Pointing observations towards the bright millimetre source J1159+292 ($S_{\text{mm}} \approx 2 \text{ Jy}$) were acquired every 30 min to ensure positional accuracy. A total on-source integration time of $\sim 5$ h was obtained in the photometry mode, achieving an r.m.s. of 0.19 mJy. Additional data from a wider area ($\sim 16$ arcmin$^2$) map of the MACS cluster (Montaña et al. in preparation; Pope et al. in preparation) were co-added to obtain a final r.m.s. of 0.17 mJy at the position of MACS1149-JD1. These observations have a similar depth to the GISMO observations at 2 mm assuming an average SMG spectral energy distribution (SED) template (Michaowski, 2008).

Figure 1. AzTEC 1.1 mm signal-to-noise map around the MACS1149-JD1 field. The white contours denote $-1.5 \sigma, -0.5 \sigma$ (dashed), and $+0.5 \sigma, +1.5 \sigma, +2.5 \sigma,$ and $+3.5 \sigma$ (solid) significance levels. The $3.5 \sigma$ AzTEC detection (black dashed 8.5 arcsec diameter circle) is 11 arcsec away from the MACS1149-JD1 position (black cross), and inside the smoothed GISMO beam (24.7 arcsec FWHM, black solid circle). The black diamonds indicate the position of potential counterparts to the (sub-)mm source from the CLASH catalogue at $z \sim 0.7$–1.6, consistent with the photometric redshift of our AzTEC source (see Fig. 3). No 1.1 mm continuum emission is detected at the position of MACS1149-JD1.

Hjorth & Watson (2010a) at $z \sim 9.6$. Alternatively, the map is $\sim 4$ times deeper if the SMG template is located at a less extreme redshift of $\sim 1$. To generate the final 1.1 mm maps from the raw data, we used the AzTEC Standard Pipeline described by Scott et al. (2008).

The distance between 15 AzTEC sources with S/N$>4$ detected in the full map and the nearest Spitzer Infrared Array Camera $4.5$ $\mu m$ sources has a $1 \sigma$ offset of 2.25 arcsec, including the overall systematic offset between the two images and the positional uncertainty in AzTEC source positions. Therefore, the astrometric accuracy of the AzTEC image is estimated to be better than 2.25 arcsec.

2.2 Ancillary data

We use public Herschel Lensing Survey (HLS; Egami et al. 2010) data in order to complete the SED of our AzTEC detection (see Section 3.1). HLS is an imaging survey of massive galaxy clusters in the FIR and submillimetre using the Herschel Space Observatory (Pilbratt et al. 2010), that includes observations from both PACS (Poglitsch et al. 2010) and SPIRE (Griffin et al. 2010) instruments at 100, 160, 250, 350, and 500 $\mu m$, with angular resolutions of $\sim 8, 13, 18, 25, 36$ arcsec, respectively.

To search for possible optical counterparts to our AzTEC detection we also use a catalogue from the Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al. 2012), which consists of HST observations of massive galaxy clusters. CLASH observations are carried out in 16 bands from the UV to the NIR (0.2–1.7 $\mu m$) and can be used to derive reliable estimates of optical–IR photometric redshifts.

1 http://herschel.as.arizona.edu/hls/hls.html
Figure 2. 30 arcsec × 30 arcsec postage stamps with HST f′160w band, Herschel 100–500 μm bands, and AzTEC 1.1 mm centred at the position of the AzTEC-detected source. The circle represents the 8.5 arcsec FWHM beam and position of the AzTEC source. The position of MACS1149-JD1 is marked with a cross. The AzTEC source is likely related to a blend of the galaxies within the circle in the HST map.

Table 1. Photometry measurements of the (sub-)mm-detected source.

| S100 μm (mJy) | S160 μm (mJy) | S250 μm (mJy) | S350 μm (mJy) | S500 μm (mJy) | S1.1 mm (mJy) | S2 mm (mJy) |
|---------------|---------------|---------------|---------------|---------------|---------------|-------------|
| 6.3 ± 0.3     | 13.3 ± 0.7    | 16.0 ± 2.0    | 9.8 ± 2.8     | 8.3 ± 3.3a    | 0.62 ± 0.17   | 0.40 ± 0.10 |

Note. aWe consider the 2.5σ detection to be an upper limit.

3 RESULTS

3.1 The (sub-)millimetre source around MACS1149-JD1

Despite achieving 0.17 mJy r.m.s. we have not found evidence of 1.1 mm continuum emission at the position of MACS1149-JD1. The closest source in our 1.1 mm map has an 11 arcsec offset from MACS1149-JD1 (see Fig. 1), and is detected with an \( S/N = 3.5 \) (\( S_{1.1 \text{mm}} = 0.62 ± 0.17 \) mJy) at RA = 11°49′34″;35 Dec=+22′44″1′.

In order to measure the positional uncertainty of this AzTEC source, we randomly insert and extract 100,000 simulated sources from our AzTEC map following the procedure described in Scott et al. (2010). These simulations use the actual AzTEC map and so include random and confusion noise and any associated biases present in the image. We find no instance of a source located at a distance ≥11 arcsec from the input position, and hence we infer that the probability that the AzTEC source is the counterpart of MACS1149-JD1 is ≤10−2, and therefore we reject the association. However, our detection lies inside of the GISMO beam (see Fig. 1), and hence both detections likely correspond to the same object. Furthermore, there are significant detections in some Herschel bands within the AzTEC beam (see Fig. 2), which supports our association.

We have obtained the Herschel fluxes at the AzTEC position by fitting a Gaussian function with the corresponding beam FWHM of each Herschel map. We fit the Herschel, AzTEC, and GISMO photometry (see Table 1) with different SED templates, including the local ULIRG galaxy Arp220 (Silva et al. 1998), an average SMG template (Michałowski et al. 2010a), and an average 24 μm-selected star-forming galaxy template, corresponding to LIRG luminosity (Kirkpatrick et al. 2012). The range for the photometric redshifts obtained from the SED fitting is \( z_{\text{phot}} = 0.7–1.6 \) (see Fig. 3). This implies that this galaxy likely lies within the lower tail of the redshift distribution of SMGs (e.g. Chapman et al. 2005; Aretxaga et al. 2007; Michałowski et al. 2012; Yun et al. 2012; Zavala, Aretxaga & Hughes 2014), although with an intrinsic luminosity and star formation rate (SFR) lower than the typical values found for this population of galaxies. From the SED fitting we derive an \( L_{\text{IR}} = 3 \times 10^{11}–1 \times 10^{12} \) L⊙ μ−1 and SFR = 50–170 M⊙ yr−1 μ−1, where μ is the lens amplification which, based on public

FF lensing models2 (e.g. Richard et al. 2014), is expected to be \( \mu = 1.2–7.4 \) (depending on redshift and the adopted model).

Our fits do not reproduce well the 2 mm data point. However, confusion noise, which has been well characterized in a shallower Gismo 2 mm-map (Staguhn et al. 2014), may contaminate the measured flux density, as well as surrounding sources. The 2 mm Gismo flux was nevertheless deboosted to the best knowledge of the 2 mm number counts (Dwek, private communication). Using our simulations, we find that the boosting factor for the AzTEC flux density is less than 5 per cent, which is smaller than the calibration error, and hence insignificant.

Searching for possible optical counterparts in the CLASH catalogue, we find five sources within the AzTEC beam (see Fig. 1),

\[ \text{L90} \quad J. \text{A. Zavala et al.} \]

\[ \text{MNRASL 453, L88–L92 (2015)} \]

\[ \text{www.stsci.edu/hst/campaigns/frontier-fields/Lensing-Models} \]
with optical photometric redshifts within the range of our estimated (sub-)mm photometric redshift. We propose that one (or a blend) of these galaxies is the real counterpart of the AzTEC and GISMO sources.

We have also detected other AzTEC sources in our extended map with S/N > 4 which also have Herschel counterparts. These sources, however, are >30 arcsec from MACS1149-JD1. The analysis of these detections will be presented in subsequent papers describing the AzTEC/LMT FF programme (Montaño et al. in preparation; Pope et al. in preparation).

3.2 Constraints on the dust properties of MACS1149-JD1

The AzTEC flux density upper limit of 0.51 mJy (3σ) at the position of MACS1149-JD1 can be used to obtain an upper limit on the dust mass ($M_d$) for this high-redshift galaxy, once a dust temperature ($T_d$) and a dust mass absorption coefficient are assumed. However, the strong dependence on $T_d$ makes it difficult to obtain meaningful constraints on $M_d$ unless reasonable temperature estimates are available. In particular, for the upper limit of $M_d$, it is more important to constrain the lower limit of the dust temperature, since lower values of $T_d$ result in higher dust masses (e.g. Hirashita et al. 2014). We compute the mass of dust by assuming a dust mass absorption coefficient $k_d(\nu_{\text{rest}}) = 0.15(850 \mu m/\lambda_{\text{rest}})^{0.3} m^2 kg^{-1}$ (Dunne et al. 2003), $\beta = 1.5$ and by removing the contribution of the cosmic microwave background (CMB) to dust heating as detailed by da Cunha et al. (2013). Finally, to examine the range of $M_d$, we assume a dust temperature range of $T_d = 30–50 K$, where $T_d$ is the dust temperature without the contribution due to the CMB heating. Using these values we estimate a dust mass limit of $M_d < 3 \times 10^7 M_\odot /\mu < 2.4 \times 10^4 M_\odot /\mu$, where the lower limit corresponds to the higher dust temperature. Correcting for the lens amplification ($\mu \approx 15$; Zheng et al. 2012), the mass dust limit corresponds to $M_d < 2.1 \times 10^6–1.6 \times 10^7 M_\odot$.

Using the SFR–$M_d$ relation found for local galaxies (e.g. da Cunha et al. 2010; Smith et al. 2012) suggests an $M_d \approx 2 \times 10^7 M_\odot$. This value is slightly higher than our upper limit, which may indicate a deficit of dust when compared to local galaxies. This has been predicted by Hjorth, Gall & Michałowski (2014) and has also been found for other high-z galaxies as Himiko at $z = 6.6$ (Ouchi et al. 2013; see also Tan et al. 2014).

We also estimate the upper limit on the intrinsic infrared luminosity ($L_{IR}$, 8–1000 μm) scaling different SED templates to our CMB-corrected 3σ AzTEC upper limit. We obtain $L_{IR} < 8 \times 10^{11} L_\odot /\mu < 1.2 \times 10^{12} L_\odot /\mu$. Correcting again for the lens amplification, this limit corresponds to $L_{IR} < 5 \times 10^{10} L_\odot - 8 \times 10^{10} L_\odot$. Using the Kennicutt (1998) relation, the total IR luminosity corrected for magnification converts to a dust-obscured star formation rate of SFR$_{IR} < 9–14 M_\odot$ yr$^{-1}$.

A proxy for the UV attenuation (A$_{UV}$) may be constrained by combining our observed limit on SFR$_{IR}$ and the SFR$_{UV}$ estimated by Zheng et al. (2012), where $A_{UV} \approx 2.5 \log$(SFR$_{IR}$/SFR$_{UV}$), as in Michałowski et al. (2012b). We obtained a limit of $A_{UV} < 2.1–2.7$ mag ($A_V < 1.0–1.2$ mag, assuming the SMC extinction curve). This limit is comparable to those derived for other Lyα and Lyman break galaxies at $z > 6.5$ (Schaerer et al. 2015; Watson et al. 2015).

4 SUMMARY

We present 8.5 arcsec FWHM angular resolution observations at 1.1 mm with the AzTEC camera on the LMT towards the $z \sim 9.6$ galaxy MACS1149-JD1, for which a possible 2 mm detection with the GISMO camera has been reported. These new observations are a factor of ~3 better in angular resolution and a factor of ~4 deeper than the GISMO observations assuming an average SMGs template (Michałowski et al. 2010a) at $z \sim 1$ (or similar depth at $z \sim 9.6$). However, despite the achieved depth of $\sigma_{1.1 \text{ mm}} = 0.17 \text{ mJy}$ in the AzTEC map, we have not found evidence of 1.1 mm continuum emission at the position of MACS1149-JD1.

A 3.5σ AzTEC detection at 11 arcsec from MACS1149-JD1, consistent with the GISMO position, is the most likely counterpart for the GISMO source. Combining the AzTEC and GISMO photometry with Herschel ancillary data we derive a $z_{\text{phos}} = 0.7–1.6$, which further indicates that this galaxy is not associated with MACS1149-JD1.

Finally, from the non-detection of the $z \sim 9.6$ galaxy MACS1149-JD1, we derive the following (3σ) upper limits corrected for gravitational lensing magnification and for CMB effects: dust mass $< 1.6 \times 10^7 M_\odot$, IR luminosity $< 8 \times 10^{10} L_\odot$, SFR $< 14 M_\odot$ yr$^{-1}$, and UV attenuation $< 2.7$ mag. These values, which represent some of the highest redshift estimations for these quantities, are consistent with measurements in other $z > 6.5$ galaxies.

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