Constraining the Thermal Dust Content of Lyman-Break Galaxies in an Overdense Field at \( z \approx 5 \)

Elizabeth R. Stanway\(^1\)\(^*,\)†, Malcolm N. Bremer\(^1\), Luke J. M. Davies\(^1\), Matthew D. Lehner\(^2\)

\(^1\)H H Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, UK
\(^2\)Laboratoire d’Études des Galaxies, Etoiles, Physique et Instrumentation GEPI, Observatoire de Paris, UMR8111 du CNRS, Meudon, 92195 France

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Abstract
We have carried out 870 \( \mu m \) observations in the J1040.7-1155 field, known to host an overdensity of Lyman break galaxies at \( z = 5.16 \pm 0.05 \). We do not detect any individual source at the \( S_{870 \mu m} = 3.0 \) mJy/beam (2 \( \sigma \)) level. A stack of nine spectroscopically confirmed \( z > 5 \) galaxies also yields a non-detection, constraining the submillimeter flux from a typical galaxy at this redshift to \( S_{870 \mu m} < 0.85 \) mJy, which corresponds to a mass limit \( M_{\text{dust}} < 1.2 \times 10^8 M_{\odot} \) (2 \( \sigma \)). This limits the mass of thermal dust in distant Lyman break galaxies to less than one tenth of their typical stellar mass. We see no evidence for strong submillimeter galaxies associated with the ultraviolet-selected galaxy overdensity, but cannot rule out the presence of fainter, less massive sources.

Key words: galaxies: high-redshift – galaxies: starburst – submillimetre: galaxies

1 INTRODUCTION
Thermal dust, interstellar gas and stellar mass all contribute to the baryon budget of the universe. In the local universe, all three components can be observed in great detail and the interplay between them studied. However, at high redshifts (\( z > 5 \)) only the most luminous, rest-frame ultraviolet-selected stellar component has been subject to detailed scrutiny.

Observations of the dust content of \( z \gtrsim 5 \) galaxies have been dominated by studies of quasar hosts (e.g. [Wang et al. 2008]) and submillimeter galaxies (e.g. [Coppin et al. 2010]) - relatively massive systems for their redshift and atypical of the star-forming galaxy population. Individual studies of far-infrared dust emission in more typical ultraviolet-luminous star-forming galaxies have been limited to unusually luminous and lensed examples (e.g. [Baker et al. 2001]), while photometrically-selected samples have been used to derive ensemble constraints from stacking analyses of UV-continuum selected samples at \( z \sim 3 \) ([Webb et al. 2003]) and galaxies selected for Lyman-\( \alpha \) emission at \( z \sim 5.7 \) ([Carilli et al. 2007]).

Constraining the dust properties in these rest-ultraviolet selected populations as a function of redshift is key to understanding the early evolution of galaxies. The ultraviolet continuum is highly sensitive to the effects of dust extinction, leading to uncertainty in derived physical properties. In particular, the clustering and star formation history of the universe at early times may be dramatically underestimated if any significant fraction of the star-forming galaxy population is omitted from rest-ultraviolet selected samples.

In our ESO Remote Galaxy Survey (ERGS, [Douglas et al. 2009]), we have identified and studied the \( z \approx 5 \) ‘Lyman break galaxy’ (LBG) population, selected for strong rest-frame ultraviolet continuum emission, in ten widely-separated fields. In two of these, J1040.7-1155 and J1054.7-1245, we have detected evidence for large scale structure in the distant universe. This comprises overdensities both in the number counts of a photometrically-selected sample and in the redshift distribution of spectroscopically confirmed galaxies, which shows a narrow (\( \Delta z = 0.1 \)) spike in source counts (Douglas et al. 2010, submitted).

We have carried out 870 \( \mu m \) observations in the J1040.7-1155 field (which hosts a galaxy overdensity at \( z = 5.16 \pm 0.05 \)) using the Large Apex BOlometer CAmera (LABOCA) at the Atacama Pathfinder EXperiment (APEX) telescope at Chajnantor in Chile in order to both probe the dust mass of the Lyman-break galaxy population and to test for the presence of ultraviolet-dark but submillimeter luminous galaxies that may form part of the same large scale structure. The unusual density of LBGs, and our extensive optical/near-infrared imaging and spectroscopy in this field, allows a simultaneous measurement of the cool dust content of a large number of spectroscopically-confirmed \( z = 5 \) galaxies.

\* email: E.R.Stanway@Bristol.ac.uk

\† Based on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile, associated with observing programmes 175.A-0706 and 083.A-0199.
In this paper we present a constraint on the dust mass of \( z = 5 \) LBGs. Throughout, we adopt a \( \Lambda \)CDM cosmology with \( (\Omega_\Lambda, \Omega_M, h) = (0.7, 0.3, 0.7) \).

### 2 Observations

Observations were carried out using the Large APEX Bolometer Camera (LABOCA) at APEX, associated with ESO programme 083.A-0190 (PI Stanway). A total of 11.7 hrs of data were collected in service mode over the period 2009 May 10th – 2009 July 29th, of which 9 hrs were spent on the target field. Data were taken using the standard spiral mapping pattern on a four-point raster to increase the area surveyed, and skydip observations were used to correct for atmospheric opacity. Precipitable Water Vapour (PWV) measurements at the site were typically 0.4-0.7 mm during observations. Pointing was checked once an hour. Standard sources CW-LEO, B13134 and N2071IR were used for pointing and flux calibration. Flux uncertainty was typically 3%.

The field was centered at \( 10^h40^m42.2^s -11^d58.0^m \) (J2000), on a \( z = 5.12 \) galaxy identified from its CO(2-1) emission in the rest-frame far-infrared (Stanway et al. 2008). Discussion of this non-LBG source is deferred to a later paper.

Unfortunately the project was not completed before the end of the semester, leading to an irregular coverage of the field, with regions of the survey area (which partly overlaps our optical imaging) significantly deeper than others. A total area of approximately \( 9.7' \times 9.7' \) was surveyed to 50%, and \( 7.7' \times 7.7' \) to 75%, of the best total coverage (figure 1).

Data were reduced using the dedicated Bolometer Array (BoA) analysis software developed to reduce LABOCA data, using an algorithm optimised to recover weak sources. LABOCA has a beam size of 18'' on the APEX telescope and the data were resampled to a pixel scale of 9'' per pixel during the reduction procedure. In common with other authors (e.g. Weiß et al. 2009), we smooth our data by convolution with the beam width in order to optimise signal to noise for point sources. The root mean square noise on the smoothed image was 1.49 mJy/beam (measured over a region with mean coverage 84%).

### 3 A Limit on the Dust Masses

Twelve spectroscopically-confirmed \( z > 5 \) Lyman break galaxies lie within the field of our LABOCA observations (shown by circles in figure 1). Of these, two lie southwards of the field centre in a region with poor flux sensitivity and are not considered further in this analysis. Two other sources are separated by a projected angular distance of only a quarter beam although there is actually a substantial line of sight distance between them, with one source lying at \( z = 5.15 \) and the second being a background source at \( z = 6.41 \) (originally selected as an I-band dropout galaxy). This is the sole outlier in our spectroscopically confirmed sample, with the remaining galaxies lying in the redshift range \( 5.1 < z < 5.5 \), with a mean redshift \( \bar{z} = 5.177 \).

None of the confirmed \( z = 5 \) galaxies in this field are individually detected. Indeed, there is, at most, one convincing 3-5\( \sigma \) detection across our field (lying well north of the region surveyed in our optical imaging and consistent with the 1-2 sources expected based on other 850\( \mu \)m surveys, Coppin et al. 2006; Weiß et al. 2009). The 18'' beam of LABOCA corresponds to an angular scale of 112 kpc at \( z = 5.18 \), and the stellar light of Lyman break galaxies in our sample is typically extended over a half-light radius of just 0.14'' (Douglas et al. 2009). We thus expect any dust emission from our distant sources to be unresolved in LABOCA imaging, and can place a 2\( \sigma \) upper limit \( S_{870 \mu m} < 3.0 \) mJy on the flux from each galaxy.

We also consider a mean stacked image constructed from a \( 40 \times 40 \) pixel \( (20 \times 20 \) beamsize) region surrounding each of the nine \( z \sim 5 \) LBGs labelled in figure 1. Eight of these show Lyman-\( \alpha \) emission lines, although only four have line equivalent widths > 30\( \AA \), sufficiently high for detection as Lyman-alpha emitters (LAEs) in typical narrow-band surveys. Since our nine sources lie in a region with near-constant coverage we use a simple mean; using a noise-weighted average changes the results by <2%, well within the statistical errors. An inspection of this stack also failed to yield a detection, with an improved upper limit on the average source of \( S_{870 \mu m} < 0.85 \) mJy (2\( \sigma \), based on the image noise, which is well fit by a Gaussian distribution). We note that contributions from sources along the line of sight between us and the \( z = 5 \) target galaxies or from the \( z = 6.4 \) background source can only increase the measured flux in the stack; hence this is a strict upper limit. Emission from line-of-sight sources offset from the targets will increase the noise levels in the image stack and such confusion may be a limiting factor on our point-source sensitivity. Again this effect acts to increase rather than decrease our upper limit.

Following Aravena et al. (2008, eqns 3 & 4), we convert our flux limit into a constraint on the dust mass of each galaxy by modelling the spectrum as a grey body, taking into account dust heating by the CMB as a function of redshift and observing frequency (a significant effect at high redshifts). We do not assume an optically-thin approximation but use the full expression. In the absence of quantitative information about the properties of dust grains at very high redshift we use the same far-infrared dust emissivity coefficient used by Aravena et al. (2008). The power law emissivity index is fixed to \( \beta = 2 \), found to fit a sample of \( z > 4 \) quasars by Priddey & McMahon (2001) and rather steeper than the \( \beta = 1.6 \) found for lower redshift quasars by Beelen et al. (2008). This steeper emissivity law is appropriate for relatively small dust grains (Desert et al. 1990) and hence may arise from evolution in the dust properties of galaxies at high redshift. Maiolino et al. (2004) found that rest-frame ultraviolet dust absorption in \( z > 6 \) sources is best described by smaller grains with production dominated by Type-II SNe, an effect also seen in \( z > 5 \) gamma ray burst host galaxies (Stratta et al. 2007; Perley et al. 2004). Altering the emissivity index from \( \beta = 2 \) to \( \beta = 1.6 \) increases the derived dust masses by a factor of 2.

Figure 2 shows our constraint on the dust mass of a typical galaxy in our sample as a function of assumed dust temperature. The LABOCA non-detection limit from our LBG stack either constrains the dust temperature in a typical UV-luminous galaxy at \( z = 5.18 \) to < 30 K or the dust mass to \( M_{dust} < 1.2 \times 10^7 M_\odot \) (2\( \sigma \)), with constraints on individual galaxies being a factor of three times weaker.

The highly lensed \( z = 2.7 \) Lyman break galaxy MS1512-cB58 has a dust temperature \( T_{dust} = 33 \) K based on fitting of
its submillimeter spectral energy distribution (Baker et al. 2003). The mean dust temperature of submillimeter selected galaxies at \( z \sim 2 \) is comparable: \( \sim 35 \) K (Chapman et al. 2003; Kovács et al. 2003). Our galaxies are less massive, and their integrated star formation rates lower, than typical submillimeter galaxies. However, the star formation intensity in their central regions is comparable – a few tens of solar masses per year per square kiloparsec (Verma et al. 2007). Hence we adopt 30 K as an estimate for dust temperature (and the resulting mass constraint) in the discussion that follows.

At this temperature, assuming the emissivity index and dust model discussed above, \( L_{\text{FIR}} = 2.8 \times 10^{12} S_{\text{870}} \text{mJy} \) for a source at \( z = 5.16 \), where \( L_{\text{FIR}} \) is the integrated far-infrared luminosity integrated between 40 and 120 \( \mu \text{m} \) in the rest-frame and measured in solar luminosities (Condon 1992) and \( S_{\text{870}} \) is the observed flux at 870 \( \mu \text{m} \) in Janskys. Hence our flux limit implies a typical \( z \sim 5 \) LBGs that neither of these populations hosts any appreciable dust. As Carilli et al. (2008) discuss, the far-infrared to radio luminosity correlation is expected to break down at high redshifts, where inverse Compton scattering off the cosmic microwave background is likely to be a significant effect.

4 DISCUSSION

4.1 LBGs at \( z \sim 5 \)

This work provides the first constraint on thermal dust emission from spectrascopically-confirmed, rest-ultraviolet continuum selected galaxies at \( z \sim 5 \). However, Carilli et al. (2007) derived an upper limit on the 1.2 mm flux of a sample of ten galaxies selected to have a flux excess consistent with strong Lyman-\( \alpha \) line emission at \( z \sim 5.7 \). Applying the same analysis used here and assuming \( T = 30 \) K, their stacking analysis limit on the typical flux of these sources, \( S_{\text{1.2mm}} < 0.7 \text{mJy} \) (2 \( \sigma \)), corresponds to a dust mass limit \( M_{\text{dust}} < 1.9 \times 10^{8} \text{M}_{\odot} \). Galaxies selected as LBGs are typically more luminous in the rest-frame ultraviolet continuum and hence believed to be older and more massive than similar sources selected for a very high Lyman-\( \alpha \) emission line equivalent width (e.g. Lai et al. 2008). However, the dust-mass constraint in this paper is now within 30\% of the tight limit on dust mass in \( z = 5.7 \) Lyman-\( \alpha \) emitters, suggesting that neither of these populations hosts any appreciable dust component.

The stellar masses of Lyman break galaxies at \( z \sim 5 \) are typically \( \sim \) few \( \times 10^{9} \) \( \text{M}_{\odot} \) (Verma et al. 2007; Stark et al. 2000). Our limit on the dust mass of these galaxies \( M_{\text{dust}} < 1.2 \times 10^{8} \text{M}_{\odot} \) at 30 K constrains their baryonic mass component in the form of thermal dust to be no more than about a tenth of the stellar component.

Interestingly, this upper limit is already comparable to the stellar mass to warm dust ratio observed in starbursts in the local universe. Hunt, Bianchi, & Maiolino (2005) studied dust emission from a small sample nearby blue compact dwarfs, which are comparable in both metallicity and star formation intensity to \( z \sim 5 \) LBGs, albeit less massive, and have emission dominated by small-grained, supernova-formed dust much like galaxies at \( z > 5 \). From SED fitting of the starbursts, Hunt, Bianchi, & Maiolino derived a stellar mass to dust mass ratio of 10 and 13 for two sources with \( Z/Z_{\odot} = 0.14 \) and 0.20 respectively. The metallicity of \( z \sim 5 \) LBGs is still poorly constrained, although estimates in the range 0.1-0.2 \( Z_{\odot} \) appear appropriate from SED fitting (e.g. Verma et al. 2007) and analysis of the rest-UV spectral slope (Douglas et al. 2010).

Lyman break galaxies at \( z \sim 3 \) are selected for rest-frame ultraviolet continuum in the same manner as the \( z \sim 5 \) LBG sample discussed here, and hence have comparable star formation intensities as submillimeter galaxies. Hence we adopt 30 K as an estimate for dust temperature (and the resulting mass constraint) in the discussion that follows.

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Lyman break galaxies at \( z \sim 3 \) are selected for rest-frame ultraviolet continuum in the same manner as the \( z \sim 5 \) LBG sample discussed here, and hence have comparable star
formation rates, and yet differ significantly in their physical properties. Lyman break galaxies at $z \sim 3$ are typically older and more massive than those at $z \sim 5$ (having had longer to evolve). They have similar or slightly higher metallicities and also appear to have slightly larger dust extinction in the rest-frame ultraviolet (Verma et al. 2007). Despite these differences, the well-studied $z \sim 3$ population provides the most direct comparison set with UV-continuum selected samples. The well-known $z \sim 3$ population provides the most direct comparison set with UV-continuum selected samples.

Individual detections of thermal dust emission have now been made in several $z \sim 3$ star-forming galaxies, generally possible by a high degree of gravitational lensing. The well-known $z = 2.7$ source MS1512-cB58 hosts a dust mass of $1.2 \times 10^7 M_\odot$ (based on the 1.2 mm flux of Baker et al. 2001), using $T=30$ K, $\beta = 2$ and correcting for lensing $\mu = 32$ and a stellar mass of $\sim 10^9 M_\odot$ (Siana et al. 2008). Similarly, the $z = 3.07$ Cosmic Eye, hosts a stellar mass $M^* = 6 \times 10^7 M_\odot$ and an estimated dust mass $M_{\text{dust}} = 2.5 \times 10^1 M_\odot$ (Coppin et al. 2007). These very low dust masses are consistent with an ensemble average estimated from a stack of submillimeter fluxes for photometrically-selected $z \sim 3$ Lyman break galaxies from the Canada-UK Deep Submillimeter Survey. Webb et al. (2003) measured a $2\sigma$ upper limit on the flux of a typical $z \sim 3$ LBG, $S_{850\mu m} < 0.4$ mJy, corresponding to a dust mass $M_{\text{dust}} < 5 \times 10^5 M_\odot$ at 30 K using the cosmology in this paper.

If the relatively low dust masses seen in $z \sim 3$ LBGs are common at higher redshifts, then significantly deeper submillimeter data will be required to detect the dust emission from $z \sim 5$ sources. However, our limit is already sufficient to challenge any paradigm in which a significant amount of the star formation at $z \sim 5$ is heavily obscured.

This argues against models in which the multi-component morphology of many rest-ultraviolet selected high redshift galaxies is analogous to the distribution of massive starburst regions seen in local ultraviolet-luminous galaxies, while the bulk of the underlying galaxy remains unseen due to heavy obscuration. The high far-infrared fluxes predicted for such embedded obscurred clumps are hard to reconcile with the tight submillimeter constraints emerging for high redshift populations (Overzier et al. 2008, 2009).

### 4.2 Structure in the J1040.7-1155 Field

While the photometric properties of individual Lyman break galaxies contributing to our analysis are rather typical of $z \sim 5$ Lyman break galaxies as a whole (Douglas et al. 2010), it is worth noting that the large scale structure properties of the field are far from typical. The redshift distribution of spectroscopically confirmed galaxies in the J1040.7-1155 field shows a 6 $\sigma$ peak relative to the mean distribution in our spectroscopic survey, lying at $z = 5.16 \pm 0.05$. The field is also overdense in photometrically selected $z \sim 5$ candidates and hosts an ultraviolet-dark $z = 5.12$ galaxy with a large mass of gas in the form of carbon monoxide (and, by inference, molecular hydrogen, Stanway et al. 2008, 2010 in prep). Six of the galaxies contributing to this analysis form part of the large scale structure in this field.

Two of these sources, objects 3 and 5 in figure 4 have tight constraints on their molecular gas masses: $M(H_2) < 1.7 \times 10^{10}$ and $M(H_2) < 2.9 \times 10^{10} M_\odot$ (2 $\sigma$) respectively, based on measurements of carbon monoxide emission at millimeter wavelengths (Stanway et al. 2008). Object 3 is confused with a bright neighbouring source in our deep {	extit{Spitzer}}/IRAC imaging of this field, but otherwise typical of Lyman break galaxies in our sample. In the case of object 5 we are also able to constrain its rest-frame optical flux based on non-detection in our IRAC imaging and estimate its stellar mass $M^* \sim 2.5 \times 10^9$ (Stanway et al., in prep). In this source, a confirmed $z = 5.116$ galaxy, the stellar mass contributes a minimum of half of the observed baryonic content of the galaxy, with the mass in molecular gas potentially comparable to this, and a contribution from thermal dust < 10% of the observed total.

These data allow us not only to study the properties of known rest-frame ultraviolet luminous sources, but also to determine whether massive, dusty sources exist within the same large scale structure at very early times. The excess of Lyman-break selected galaxies may well be tracing out massive large scale structures in which the majority of baryonic material is undetected in the ultraviolet (Stanway et al. 2008). If massive submillimeter galaxies preferentially occupy strong peaks in the matter density distribution (Blain et al. 2004), we might expect to detect an excess such galaxies in this field. Such behaviour has been observed using LABOCA by Beelen et al. (2008) who identified a possible overdensity of submillimeter galaxies apparently associated with strong Lyman-$\alpha$ emitting sources forming a protocluster at $z \sim 2.4$, by Ivison et al. (2000) who observed massive SCUBA galaxies clustering with Lyman break galaxies in the environs of a $z = 3.8$ radio galaxy, and by Aravena et al. (2010) who observed BzK galaxies clustering with MAMBO-selected sources at $z \sim 2$. Given the current lack of information on typical luminous lifetimes, dust properties, clustering scales and mass scales of $z \sim 5$.
LBGs, submillimeter and gas-dominated galaxies, it is impossible to make a quantitative prediction for the number of submillimeter sources expected in an overdensity of Lyman break galaxies. However there is no evidence for this field being overdense in submillimeter galaxies at any redshift.

At dust temperatures of ~30-35 K the lack of 3σ detections for continuum sources in our field implies a dust mass limit of ~ 2 – 4 x 10⁶ M☉ at z ∼ 5, ruling out the presence of a massive UV-obscured active galaxy or submillimeter galaxy comparable to others seen at high redshift (see compilation in Solomon & Vanden Bout 2005). However, we caution that our constraints on individual sources are weak (and depend on the assumed dust temperature). We cannot rule out a substantial population of cooler, less massive or less dusty sources in this field. The apparent lack of massive evolved systems at this redshift may indicate that galaxies, even those in apparently overdense regions, may have a more complex history than simply growing into massive galaxies observed locally.

5 CONCLUSIONS

We describe 870 µm observations undertaken using LABOCA and targeting a field known to host an overdensity of Lyman break galaxies at high redshift. Our main conclusions can be summarised as follows:

(i) No individual galaxy is detected in our LABOCA observations, to a a 2σ upper limit S_{870µm} < 3.0 mJy.

(ii) By stacking nine spectroscopically confirmed z ∼ 5.2 galaxies in this field, we are able to constrain the thermal dust emission in a typical Lyman break galaxy at this redshift to S_{850µm} < 0.85 mJy, corresponding to a dust mass M_{dust} < 1.2 x 10⁷ M☉ (2σ) at a dust temperature of 30 K.

(iii) These observations place an upper limit on the thermal dust fraction in a typical LBG at z ∼ 5 of ∼ 10% of the stellar mass.

(iv) We see no evidence for an excess of heavily-obscured massive starburst galaxies associated with a large scale structure at z = 5.16 in this field.

Deeper submillimeter observations are required to better constrain the dust properties of galaxies at high redshift. Our observational programme to characterise z ∼ 5 galaxies is continuing, with particular emphasis on both this field and a second overdense region. We note that the Atacama Large Millimeter Array (ALMA) will have a transformative effect on these studies, making dust continuum detections in typical, unlensed Lyman break galaxies accessible for the first time. However the small field of view of ALMA at submillimeter wavelengths (just 13 arcseconds at 250 GHz) will reduce its effectiveness for large scale mapping of the relatively sparse high redshift galaxy population.

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