The sub-mm properties of Lyman Break Galaxies

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Background: some of the first HST (WFPC2) images of LBGs Lowenthal+97
Talk in a nutshell

1. The Star Formation Rate Density of the Universe — *why LBGs and knowing their dust content matter so*

2. Dissecting the IRX-Beta relation at z~3 and beyond:
   - deep submm stacking with SCUBA2 & Herschel
   - resolved observations of $L_{\text{IR}}$, $L_{\text{UV}}$ and UV-spectral slope (unlensed!)

3. Conclusions and food for thought
We can identify swathes of “normal” star-forming galaxies at $z>3$ using UV colours near the redshifted 912Å Lyman-continuum break (Steidel+96) — without the need for time-consuming spectroscopy.

Figure from Madau&Dickinson 2014
We need a robust way to transform UV luminosity densities into total SFRDs.

We know that rest-frame UV-based measurements will suffer from dust extinction - so we need to account and correct our UV-SFRs for that.

One way: using a simple attenuation-based correction (Meurer or Calzetti etc.)

Figure from Madau&Dickinson 2014
Effective dust extinction: IR vs. UV view

SFR density measured in the UV (uncorrected for dust attenuation) and IR

Direct (IR) and indirect (UV-slope/SED) estimates of the dust attenuation in magnitudes as a function of redshift

Data from Burgarella+13 comparing FIR and FUV luminosities

Data based on UV slopes/local attenuation-reddening laws (Meurer+99; Calzetti+00) or UV-optical SSP/SED fits

Figures from Madau&Dickinson 2014
Hidden Star Formation at z~3

General trend: more luminous galaxies tend to be more obscured.

But a UV-faint galaxy could be intrinsically faint (low SFR) or just heavily obscured (high SFR) - how do we know which scenario?

Most direct way to assess the amount of dust is to probe it directly via FIR emission (redshifted into submm).

Problem: limited by instrument sensitivity and dust is faint for typical LBGs!

NOTE: $L_{bol,dust}$ (here) is estimated via local SFG SEDs the Meurer+99 dust extinction law - it is not measured directly!

Figure from Adelberger & Steidel (2000)
Some challenging first attempts to measure FIR emission from LBGs (with SCUBA)

null/weak stacked detections of LBGs: Webb+03

The few submm detections tend to be for reddest LBGs (Chapman +00+09 )

Galaxies with highest UV-SFRs have total SFRs 6x larger than that estimated from the UV alone (Peacock+00)
...some examples of successful stacking of $z \sim 2-3$ LBGs in Spitzer & Herschel data

$z \sim 3.7$ LBG stacking with Spitzer+Herschel/SPIRE (Lee +12) — a hint that the IRX is weaker at $z \sim 3.7$ than that seen at $z \sim 2$ by Reddy+12?

$z \sim 2$ LBG stacking with Spitzer +Herschel/PACS (Reddy+10+12)

Stacking $z \sim 3$ IRAC-detected LBGs in 24um, radio, 1.1mm Magdis+10; Rigopoulou+10 (..but biased to most massive LBGs)
…and with the SCUBA2 Cosmology Legacy Survey + public *Herschel* HerMES data

**SC2CLS 850um map of UKIDSS-UDS: now ~700 arcmin², rms~0.9mJy (Geach+16)**

**Herschel+SCUBA2 250-850um (deblended) photometry fitting with a library of star-forming galaxy SEDs from Swinbank+14: confirms LBGs have LIR~LIRG-to-ULIRG level IR luminosities/SFRs (Coppin+15)**

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Number of LBGs</th>
<th>S850 (mJy)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>z=3</td>
<td>4201</td>
<td>0.25 +/- 0.03</td>
<td>8.5</td>
</tr>
<tr>
<td>z=4</td>
<td>869</td>
<td>0.41 +/- 0.06</td>
<td>6.4</td>
</tr>
<tr>
<td>z=5</td>
<td>68</td>
<td>0.88 +/- 0.23</td>
<td>3.8</td>
</tr>
</tbody>
</table>

80”x80” thumbnail images of the S/N of average 850um flux centred on LBG positions at z~3, 4 & 5 (Coppin+15)
Capak+15 find 5<z<6 ALMA-measured dust emission in 9 ALMA-detected LBGs to be ~10x weaker than expected

Seems ok at z~2! (Reddy +12)

Stacking vs. individual detections

Coppin+15 stacks of z~3,4,5 LBGs at 850um are consistent with the Meurer +99 relation (see also Alvarez-Marquez+16/ Burgarella’s talk)

What’s going on?! is there some dependence on galaxy mass or ? (e.g. Alvarez-Marquez+16; Bouwens+16)

Coppin+15 & Geach/Coppin et al. in prep.
Trying to directly detect the dust in “typical” z~3 LBGs

ALMA Cycle2 850um continuum obs of 10 z=3.1 LBGs in SSA22 from Hine+16

Koprowski+16 find a 3-sigma stacked detection of 9 of our LBGs (67 +/- 23uJy), with one individual 192 +/- 57uJy detection and resolved in 0.45” ALMA beam!… interestingly, it is our most massive LBG (3x10^{10}Msun) —> hint of mass dependence (eg. Bouwens+16)?

SFR_{uv}=19 \text{ Msun/yr} \quad SFR_{IR}=15 \text{ Msun/yr}

HST with ALMA contours

HST smoothed to ALMA resolution

Gaussian shape reveals ALMA data are resolved

ALMA Band 7

ALMA Band 7

RGB colour image

Yamada et al.

Steidel et al.

Koprowski+2003

Coppin et al.

Steidel et al.

Figure 1. Panel 1: The ALMA Band 7 contours overlaid on the HST F814W image. The contours are 2, 2.5, 3, 3.5 and 4 \sigma.

Panel 2: The RGB plot for SSA22a-C16 with red, green and blue colors representing emission from a (lensed) galaxy with blue UV color at z=70 km s^{-1} Mpc^{-1}.

Panel 3: The IRX map with a pixel size of 0.05 arcsec. The IRX peaks at (PA=-33.32 deg) is shown in the top left corner.

DATA AND OBSERVATIONS

Imaging Spectrometer (LRIS), on Keck (with a 5-10% uncertainty on the absolute flux calibration)

To image the visibilities we used the CASA calibration package.

We stack the nine non-detections to measure the average flux density of these sources. Stacking is performed in the uv-plane: the calibrated measurement set is split into nine individual measurement sets, phase shifted to a common coordinate system 4.4.0.

Calibration firstly concatenated into a single measurement set. Calibration firstly was performed, with the phase-only gain solutions applied on-the-fly to individual antennas, channel edges, etc. The bandpass calibration was then done by the water vapour radiometers corrections and initial noise. Only one target is detected (SSA22a-C16 at z=3–5, with canonically resolved ALMA data).

This relative geometry of the UV and dust emission, seen at different lines of sight, is what may cause a scatter in the IRX values of high-redshift galaxies. In this Letter we present new 870 µJy beam ALMA Band 7, ALMA Cycle2 850um DATA AND OBSERVATIONS 2015 observations were split into 2014 June 30 and 2015 April 29 as a part of Cycle 2. The observations were selected LBGs typically guided the sensitivity requirements of the follow-up ALMA. Combined with a (lensed) galaxy with blue UV color at z=00.

In order to maximize sensitivity, the goal being to measure an integrated flux density of 15 Msun/yr.

The RGB plot for SSA22a-C16 with red, green and blue colors representing emission is resolved on this scale.
Key Findings:
1) Averaged over the galaxy — our resolved LBG lies significantly below the Meurer+99 relation
2) Our resolved IRX map shows 0.5<IRX<1.5 (up to factor ~3 off from integrated value)
3) The Meurer+99 relation is based on starburst nuclei, starburst rings, blue compact dwarfs and blue compact galaxies — with obscuring dust co-located with the young stars. High-z galaxies are different (clumpy/mergers/turbulent/complex geometry)- so is unlikely to describe them!

Exploring the variation of IRX within a single z~3 LBG
Complete resolved information of IRX and Beta reveals consistency within the scatter of Meurer+99 or SMC relations

IRX-Beta integrated over the LBG lies significantly below the Meurer+99 relation — but NOW with resolved IRX and resolved Beta shows that it is ~within the (large) scatter of Meurer99 or perhaps hinting at an SMC-like relation!
Take home points & some (collated) thoughts from meeting so far

• We should care that the dust and stars are not well mixed in high-z sources….Meurer99 is based on the idea that they are well mixed (dust treated like screen)!

• Need to take into account what a measured Beta is telling us: i.e. the average slope you get from several different stellar pops (not necessarily dust-obscured ones)

• Interesting that ‘stacked’ single-dish IRX results seem to agree with Meurer99 relation, but direct individual (integrated) observations of LBGs don’t - some bias we aren’t understanding?

• A way forward?
  • resolved stellar and dust mapping of a larger sample of LBGs in mass slices to explore this further…and Is this effect seen in simulated galaxies (Jim Geach talk)?