The Submillimetre properties of Lyman-break galaxies at z=3-5

Kristen Coppin
Centre for Astrophysics Research
University of Hertfordshire, UK

Background: some of the first HST (WFPC2) images of LBGs Lowenthal+97
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Stamps: HST WFC3/IR F160W w/ ALMA 870um contours (Koprowski in prep., Stach+19)
History of cosmic star formation

Figure from Madau & Dickinson (2014)
Most of the energy from star forming galaxies at z<2 is absorbed and re-radiated by dust

...but the total amount of SF missed from UV surveys at such high-redshifts is still uncertain

SFRD measured in the UV (uncorrected for dust) and IR

We can very efficiently identify “normal” star-forming galaxies at z>3 using UV colours near the redshifted 912 Angstrom Lyman-continuum break (e.g. 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 data suffers from dust obscuration - we need to account for this and correct the UV-SFRs either by:

\[ \text{Unobscured SF (traced by HST)} + \text{Obscured SF (traced by Spitzer)} = \text{TOTAL Star Formation (HST/CTIO/ALMA/VLA)} \]
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1) measuring the dust directly: e.g. Laporte+17 detects dust out to z=8.4 in a gravitationally-lensed galaxy with ALMA… but it’s hard!
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2) using a simple attenuation-based correction of the UV flux (e.g. Meurer+99 or Calzetti+00)

…but does this still hold at $z>3$?

Meurer, Heckman & Calzetti+99
Stacking z~2-4 LBGs with *Spitzer & Herschel*

**Stacking z~2 LBG stacking with Spitzer+Herschel/PACS (Reddy+12)**

**Stacking z~3 LBG stacking with Spitzer+Herschel/PACS (Reddy+12)**

**Stacking z~3.7 LBG stacking with Spitzer+Herschel/SPIRE (Lee+12) — showing a general consensus with Meurer+99**

**Stacking z~3 IRAC-detected LBGs in 24um, 1.1mm, radio by Magdis+10; Rigopoulou+10 (..but for most massive >10^{11}M_{Sun} LBGs)**
Dust-obscured SF in ~5000 typical z~3-5 LBGs revealed by SCUBA2 Cosmology Legacy Survey + *Herschel* HERMES

Herschel+SCUBA2 250-850um fit with SF galaxy template SEDs (Swinbank+14): *confirms LBGs have L_{IR}~LIRG-to-ULIRG level luminosities* on average (Coppin+15)

SC2CLS 850um map of UKIDSS-UDS: 700 arcmin$^2$, rms~0.9mJy (Geach+17)

80”x80” thumbnail S/N images of average 850um flux centred on ~5000 LBGs at z~3, 4 & 5 (Coppin+15)
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n_{LBGs}=4201

n_{LBGs}=869

n_{LBGs}=68

S_{850}=0.25+/-0.03 mJy (S/N=8.5)

S_{850}=0.41+/-0.06 mJy (S/N=6.4)

S_{850}=0.88+/-0.23 mJy (S/N=3.8)

10hrs 5-sigma SAFARI

SPICA will open up the rich mid-IR spectral diagnostics in “normal” star-forming galaxies at z>3: PAHs, ionised gas tracers, mid-IR continuum, etc.
Surprise: typical z~3 LBGs are quite dusty!
Comparison of obscured vs. unobscured SFR at z~3

Trend: reddest LBGs are more dust obscured, with average $L_{\text{IR}}/L_{\text{UV}}$ increasing with mass and with the range greatest for lower-mass systems

(See also eg. Buat+12, Hilton+12, Heinis+14, Alvarez-Marquez+16, Bouwens+16, Bourne+17, Barisic+17, Whitaker+17, Reddy+18, McLure+18 etc..)
The Local IRX-Beta seems to hold out to $z \sim 5$

Koprowski+18 carefully re-stacked in final SCUBA2 maps $z \sim 3, 4, 5$ LBGs:
- **consistent** with the Meurer+99 relation
- **no z-evolution** (see also McLure+17)

My postdoc Maciej Koprowski (now in Torun, Poland)
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Capak+15, Nat. find 5$<z<6$ ALMA-measured dust emission in 9 ALMA-observed LBGs to be $\sim 10x$ weaker than expected - do $z \sim 5$ LBGs follow a different dust law?

Question for SPICA - what is the dust chemistry and its evolution over cosmic time? Nagao’s review talk & Fernandez Ontiveros
Is the scatter seen surprising?...not really

Have to keep in mind that Meurer+99 is based on starburst nuclei, starburst rings, blue compact dwarfs and blue compact galaxies — co-located stars+dust — to 1st order: a foreground screen of dust.

High-z galaxies are different (clumpy/mergers/turbulent/complex geometry; e.g. Ivison+11; Casey+14; Simpson+15; Rujoparkan+16; Hodge+16) - so this local relation is unlikely to describe them well.

Theory predicts IRX-beta scatter in the following ways (e.g. Narayanan+17; Popping+17)
Exploring the scatter in IRX-Beta: new ALMA detections of z~3 LBGs

We used 716 ALMA maps in the UDS field centred on SCUBA2 SMGs (Stach+19):
- 41/250 (16%) z~3 LBGs match w/in 0.6" to a S/N>4.3 ALMA detection (~0.3mJy rms)
- Properties of the submm-detected LBGs:
  - $S_{870} \sim 1-11$ mJy (median \sim 4 mJy) - LBGs with redder UV continuum slope
  - total SFRs\sim 100-900 M_{\odot} - most massive (>2\times 10^{10} M_{\odot})
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Higher fraction of massive LBGs are individually ALMA detected (probably reflecting the SFR-stellar mass relation)
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We are now mapping the unobscured and obscured SF in LBGs at z~3

Koprowski et al. (in prep.)
See also Koprowski+16
Work for SPICA

- We have now constrained the rest-frame far-IR emission in *optically selected* LBGs at z>3 both statistically (stacking) and now directly with ALMA.

- This is a population very well studied in the optical (e.g. Steidel, Shapley et al.)

- Missing information: the mid-IR. SPICA will provide access to this, and now we have a good idea of expected flux from well-constrained SEDs.

- Spectroscopy will reveal mid-IR dust properties, ISM conditions, role of AGN, etc.

- Samples of *gravitationally lensed* LBGs (μ>10x) like the z=3 Cosmic Eye (Smail+07, Coppin+07) will allow even more detailed studies (e.g. access to H₂ lines).

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*Figure 6.* Comparison of mid-IR spectra (normalized to the 6.7 μm continuum) of the Cosmic Eye, cB58 (Siana et al. 2008), an SMG composite (Menéndez-Delmestre et al. 2009), and a local starburst composite (Brandl et al. 2006). These galaxies span 3 orders of magnitude in luminosity in $L_{\text{IR}}$ (10^{10}–10^{13} $L_\odot$). The mid-IR spectra of the LBGs (Cosmic Eye and cB58) and the local starburst composite are similar. However, the $L_{7.7}/L_{6.2}$ ratio of the SMGs is markedly higher than in the LBGs or local starbursts.