What are the Physical Characteristics of Dust in LBGs at $z > 5$?

Dusting the universe ... from the very beginning

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Outline of the Talk

• **Introduction**
  • The FIR + sub-mm Emission of Low-Z/z Galaxies and High-z LBGs @ 5 < z < 8
    o Introduction
    o Selection
    o Method
    o Results

• **Other ongoing project at IRAM**
Making use of the full SED

Relative flux (normalized to 10 times the Solar luminosity)

- Ultraviolet + optical
- Infrared

$A = 0.55 \mu m$

$1 \times 10^{-1}$

$5 \times 10^{-2}$

$1 \times 10^{-2}$

$5 \times 10^{-3}$

$1 \times 10^{-3}$

$5 \times 10^{-4}$

$0.5$ $1.0$ $5.0$ $10.$ $50.$ $100.$ $500.$ $1000.$

Wavelength [\mu m]

$log(\frac{L_{IR}}{L_{UV}})$

\begin{align*}
A_{UV} & = 0.000 \\
A_{0.55 \mu m} & = 0.001 \\
A_{0.55 \mu m} & = 0.005 \\
A_{0.55 \mu m} & = 0.01 \\
A_{0.55 \mu m} & = 0.05 \\
A_{0.55 \mu m} & = 0.1 \\
A_{0.55 \mu m} & = 0.5 \\
A_{0.55 \mu m} & = 1.0 \\
A_{0.55 \mu m} & = 2.0 \\
A_{0.55 \mu m} & = 3.0 \\
A_{0.55 \mu m} & = 5.0
\end{align*}

$A_{UV}^{best fit}$

Takeuchi et al. 2005

Cucciati et al. 2012

Bouwens et al. 2009

redshift
Outline of the Talk

• **Introduction**

• **The FIR + sub-mm Emission of High-z LBGs @ 5 < z < 9**
  - *Introduction*
  - *Selection*
  - *Method*
  - *Results*

• **Other ongoing project at IRAM**
• We do not understand the dust emission of high-redshift Lyman break galaxies (LBGs)

• Their dust attenuation is too low compared to what is expected from their UV slope $\beta$. 
Ferrara et al. (2017): « This marked deviation from the local IRX-β relation can be explained by the larger molecular gas content of these systems. While dust in the diffuse interstellar medium attains relatively high temperatures ($T_d = 45K$ for $0.1 \mu m$ grains, smaller grains can reach $T_d = 60 K$), a sizable fraction of the dust mass is embedded in dense gas, and therefore remains cold. »

Faisst et al. (2017): « We propose that radiation pressure in these highly star-forming galaxies causes a spatial offset between dust clouds and young star-forming regions within the lifetime of O/ B stars. These offsets change the radiation balance and create viewing-angle effects that can change UV colors at fixed IRX. »
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Hi-z LBGs

- All these 16 galaxies are Lyman Break galaxies (LBGs)
- They have spectroscopic redshifts
- Some of them are detected in FIR-submm. We use them to estimate a stacked IR template
- Some are not detected in FIR-submm. We apply the above template to these objects.
- The last one is MACJD1149 @ \( z = 9.1096 \)

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MACSJJD1149 | 11:49:34 | 22:24:46 | 9.11 |

Burgarella, Hirashita et al. (in prep.)
The onset of star formation 250 million years after the Big Bang @ z = 9.1

Takuya Hashimoto*,1,2, Nicolas Laporte3,4, Ken Mawatari1, Richard S. Ellis3, Akio. K. Inoue1, Erik Zackrisson5, Guido Roberts-Borsani3, Wei Zheng6, Yoichi Tamura7, Franz E. Bauer8,9,10, Thomas Fletcher3, Yuichi Harikane11,12, Bunyo Hatsukade13, Natsuki H. Hayatsu12,14, Yuichi Matsuda2,15, Hiroshi Matsuo2,15, Takashi Okamoto16, Masami Ouchi11,17, Roser Pelló4, Claes-Erik Rydberg18, Ikko Shimizu19, Yoshiaki Taniguchi20, Hideki Umehata13,20,21, Naoki Yoshida12,17

Figure 1 | ALMA [OIII] contours and spectrum of MACS1149-JDL. (a) Zoom on an HST image (F606W) with the ALMA [OIII] contours overlaid. Contours are drawn at 1σ intervals from ±3σ to ±6σ.
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• Other ongoing project at IRAM
Very limited amount of data available for Hi-z LBGs at z > 5.
How can we densify the information, obtain a more regular sampling?
1) Get information on the **blue** side of the dust IR emission

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**Fig. 1.** Metallicity distribution of the DGS sample from $12 + \log(O/H) = 7.14$ to 8.43. Solar metallicity is indicated here as a guide to the eye. The pre-*Herschel* star formation rate (SFR) distribution is also indicated by the colour code. They have been converted from $L_{\text{IR}}$(Spitzer) with the *Kennicutt* (1998) law, and are given in *Madden et al.* (2013). When no IR data was available, Hα or Hβ emission lines were used and converted to SFR (*Kennicutt* 1998). The dashed cells indicate that none of these data were available for the galaxy. The most actively star-forming galaxy (in red) corresponds to the starburst luminous infrared galaxy (LIRG) Haro 11.
2) We want to densify the SED to constrain the IR SED of these objects.
Code Investigating Galaxy Emission (CIGALE)

Dusting the universe, Tucson, AZ - denis.burgarella@lam.fr

http://cigale.lam.fr
Is CIGALE faintly related to the topic of this conference...?

What is CIGALE?

Denis Burgarella (France)
Médéric Boquien (Chile)
Yannick Roehlly (France)
Laure Ciesla (France)
Véronique Buat (France)
### Methodology

<table>
<thead>
<tr>
<th>SAMPLES</th>
<th>Individual fit on Hi-z LBG and Low-zZ samples</th>
<th>Combined Hi-z SEDs (normalized at 200um)</th>
<th>Get 1 IR template for Hi-z LBG (+ γ and q&lt;sub&gt;PAH&lt;/sub&gt; from low-zZ)</th>
<th>Fit 1 IR template</th>
<th>Fit all individual Hi-z LBGs using the best-fit IR model</th>
<th>Get Physical Parameters for all Hi-z LBGs</th>
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<td>γ</td>
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</table>
Fit on the composite IR SED using Draine & Li models

Best model for LBG at $z = 0.0$. Reduced $\chi^2=0.16$
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Examples of Probability Distribution Function from the analysis

![Probability distribution function of sfh.age for CLM1](Image1)

- Age

![Probability distribution function of stellar.m_star for HZ2](Image2)

- Stellar mass

![Probability distribution function of attenuation.E_BVs for WMHS](Image3)

- $E_{B-V}$

![Probability distribution function of sfh.sfr for HZ4](Image4)

- SFR

![Probability distribution function of attenuation.FUV for HZ10](Image5)

- $A_{FUV}$

![Probability distribution function of dust.mass for HZ10](Image6)

- Dust mass

05/03/2019

Dusting the universe, Tucson, AZ - denis.burgarella@lam.fr
1. At low-Z & low $M_{\text{star}}$, low dust content $\Rightarrow$ very low $M_{\text{dust}}/M_{\text{star}}$. Low-Z dust production only controlled by stellar sources.
2. When a critical metallicity is reached, dust growth by metal accretion on the ISM dust grains becomes the major process for building up dust mass. Dust mass increases without significant consumption of the gas reservoir or star formation.
3. Dust growth processes saturate when all available metals are locked up in grains. In the meantime, star formation continues, consuming the gas reservoir and increasing the stellar mass. $\Rightarrow$ decreasing sSFR, decreasing dust-to-stellar mass ratio.
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Remy-Ruyer et al. (2015)
Results on Hi-z LBGs from our analysis

- CLM 1 @ z = 6.2
- MACSJD1149 @ z = 9.1
Results on Hi-z LBGs from our analysis

- CLM 1 @ z = 6.2
- MACSJD1149 @ z = 9.1
Results on Hi-z LBGs from our analysis

First generation of stellar dust grains (before build-up in ISM)

CLM 1 @ z = 6.2
MACSJD1149 @ z = 9.1

New models under developments in LAM, France with (Ambra Nanni & Hiroyuki Hirashita, ASIAA, Taiwan)
Fig. 5 Time evolution of silicate and carbonaceous dust of different origin with destruction in the ISM by SN shocks (left) and without destruction (right). Even without SN destruction, the stardust mass at the present time is smaller than the total interstellar dust mass in the LMC, $1.1-2.5 \times 10^6$ $M_\odot$ (gray line). Only with dust growth by accretion in the ISM, we can reproduce the present day interstellar dust mass in the LMC. However, the fraction of stardust is higher in the LMC compared to our Galaxy ($3.4-7.7\%$ vs. $1.5-2\%$).
We might be witnessing the destruction of the first dust grains in these early galaxies on a timescale of the orger of 250 Myrs.
The Summary...

• We have been able to constrain the Physical characteristics of LBGs at $5 < z < 9$
• We have been able to fit the $z = 9.1$ object with a [OIII]88um emission and this galaxy appears to lie in a very early phase of dust formation, probably forming the first stellar dust grains via supernovae (maybe too early for AGB dust).
• Another sample of $5 < z < 8$ LBGs are a little bit mode evolved and we can witness an evolutionary sequence of dust formation.
• Our data suggest that we have constrained the dust destruction of this early dust grains through an age sequence.
• LBGs with weird characteristics are likely to be (relatively) old stellar populations in the process of destructing their dust grains.
• We need more observations, in the same redshift range (ALMA, NOEMA, JWST) and at higher redshifts (Origins Space Telescope).
• Everything presented here is based on models developed for the local universe. Are they valid at $z > 6$? We need to develop specific models. We have started to work... but it takes time and a lot of effort!

... and The End