Direct constraints on UV attenuation, dust-obscured star formation, and dust mass of z=6.5-7.5 galaxies

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• Introduction, motivation
• New constraints on z>6 star-forming galaxies
• Conclusions

→ Schaerer & de Barros 2014, in prep
Introduction

Cosmic star formation rate history

→ review of Madau & Dickinson (2014)

Major unknowns:
• contribution of different galaxy populations
• dust-obscured star formation
• attenuation correction
Measurement of dust attenuation

Main methods:
1. Balmer decrement: Hα/Hβ ratios measured out to z~2 (ground-based + HST WFC3 grism)
2. IR/UV ratio
3. UV slope β: only method so far at high redshift (LBGs, LAEs)
Results from IR / Herschel

Mean attenuation as function of redshift

Burgarella et al. (2014)
Results from IR / Herschel

Stellar mass -- dust attenuation correlation
• «universal » for all galaxy types?
• also valid at high $z$?

Heinis et al. (2014)
Pannella et al. (2014)
+ many others

Tentative relation for LBGs @ $z\sim6-8$ !?
Schaerer & de Barros (2010)
Results from IR / Herschel

**z~2 LBGs**: Reddy et al. (2012)

**z~2 DOGs**: Penner et al. (2012)

**Lensed z~2-3 SFGs**: Sklias et al. (2014)
Adequacy of the UV slope method at high-z?

• Empirical correlation of IRX (=IR/UV) versus UV slope $\beta$ in nearby star-forming galaxies: « Meurer law » (Meurer et al. 1992, Takeuchi et al. 2012)
• Correlation is reproduced by models with:
  • $SFR=\text{const, age}>100$ Myr
  & solar metallicity
  $\rightarrow$ Intrinsic slope $\beta_0=-2.23$
• Calzetti attenuation law

• Assumptions probably invalid for high-z galaxies:
  • Younger populations on average
  • Non-uniform/bursty SF histories
  • Metallicity $<\text{solar}$
  $\rightarrow$ Revised « Meurer law »
  $\rightarrow$ Higher UV attenuation for given slope $\beta$

de Barros et al. (2014), Castellano et al. (2014 + Poster)
Inadequacy of the UV slope method at high-z: Higher UV attenuation at high-z?

LBGs at z~3-7:

• Large LBG sample from z~3-6: SFR increased by ~2-3 (de Barros et al. 2014)
• \(z_{\text{spec}}\)~2.8-3.8 sample (14 objects with known metallicity):
  SFR higher by factor 2-4 (Castellano et al. 2014)

• SFR density increased by factor \(~1.2 – 4\) between z~7 and 3 (Schaerer & de Barros 2014)
• UV attenuation versus z in agreement with extrapolation of IR/UV measurement at z<3 (Burgarella et al. 2014)

→ Next step: direct measurement of IR emission

Schaerer & de Barros (2014)
First hints on dust in «normal» z>6 galaxies with IRAM and ALMA

z=5.2 Herschel Lensing Survey (Combes et al. 2012)

Lensed galaxies:
- z=4.9 MS1248arc: Livermore+ 2012
- z=6.56 HCM6A: Boone+2007
- z=7 A1703: Schaerer+2014

Blank fields:
- z=6.56 LAE Himiko: Ouchi+2013
- z=6.96 LAE IOK-1: Ota+2014
- z=8.2 GRB090423: Walter+2012 Berger+ 2014
- z=7.5 Finkelstein+2013 object

Strongly lensed objects from Herschel Lensing Survey (Sklias et al. 2014)

Predicted \( L_{\text{IR}} \) of \(~1400\) LBGs from \( z\sim3.4 \) – 7 (Schaerer+ 2013)
Our sample

Lensed galaxies:
- $z=6.56$ HCM6A $\mu=4.5$: Boone+2007
- $z=7$ LBG in Abell 1703 $\mu=9$, from Bradley+ 2012

Blank fields:
- $z=7.5078$ LBG from Finkelstein+2013
  $\rightarrow$ New IRAM observations

- $z=6.56$ LAE Himiko: Ouchi+2013
- $z=6.96$ LAE IOK-1: Ota+2014
  $\rightarrow$ Recent ALMA observations

Finkelstein+ 2013

Bradley+ 2012
IRAM and ALMA observation

- MAMBO-2 @30m, 1.2mm: $\sigma = 0.36$ mJy, 4h on-source (Boone+2007)
- WIDEX@PdBI: $\sigma_{\text{cont}} = 0.09, 0.12, 0.16$ mJy/beam (Walter+2012, Schaerer+2014)
- GISMO@30m, 2mm: $\sigma_{\text{cont}} = 0.15$ mJy (Schaerer+2014)
- ALMA band 6, cycle 0 data: $\sigma_{\text{cont}} = 0.017 - 0.021$ mJy/beam (Ouchi+2013 Ota+2014)

$\rightarrow$ No detection in continuum and [CII] 158micron

$\rightarrow$ Limits on IR luminosity and dust mass: assuming $T_d = 35$ K, $\beta = 2$, including correction for CMB heating

<table>
<thead>
<tr>
<th>Source</th>
<th>$z$</th>
<th>$\nu$ [GHz]</th>
<th>$\text{rms}_{\text{cont}}$ [mJy beam$^{-1}$]</th>
<th>$\sigma_{\text{line}}$ [mJy beam$^{-1}$]$^c$</th>
<th>$L_{\text{[CII]}}$ 10$^8$ [L$_\odot$]</th>
<th>$L_{\text{IR}}(T_d = 25)$ 10$^{11}$ [L$_\odot$]</th>
<th>$L_{\text{IR}}(T_d = 35)$ 10$^{11}$ [L$_\odot$]</th>
<th>$L_{\text{IR}}(T_d = 45)$ 10$^{11}$ [L$_\odot$]</th>
<th>$\mu$</th>
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<tbody>
<tr>
<td>A1703-zD1</td>
<td>6.8$^a$</td>
<td>241.500</td>
<td>0.165</td>
<td>1.517</td>
<td>&lt; 2.55/$\mu$</td>
<td>&lt; 3.96/$\mu$</td>
<td>&lt; 7.32/$\mu$</td>
<td>&lt; 14.38/$\mu$</td>
<td>9.</td>
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<tr>
<td>z8-GND-5296</td>
<td>7.508</td>
<td>223.382</td>
<td>0.124</td>
<td>1.824</td>
<td>&lt; 3.56</td>
<td>&lt; 3.84</td>
<td>&lt; 6.65</td>
<td>&lt; 12.67</td>
<td></td>
</tr>
<tr>
<td>IOK-1$^b$</td>
<td>6.96</td>
<td>238.76</td>
<td>0.021</td>
<td>0.215</td>
<td>&lt; 0.38</td>
<td>&lt; 0.53</td>
<td>&lt; 0.96</td>
<td>&lt; 1.87</td>
<td></td>
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<tr>
<td>HCM6A$^c$</td>
<td>6.56</td>
<td>251.40</td>
<td>0.16</td>
<td>0.849</td>
<td>&lt; 1.36/$\mu$</td>
<td>&lt; 3.47/$\mu$</td>
<td>&lt; 6.49/$\mu$</td>
<td>&lt; 12.81/$\mu$</td>
<td>4.5</td>
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<td>Himiko$^d$</td>
<td>6.595</td>
<td>250.00</td>
<td>0.017</td>
<td>0.167</td>
<td>&lt; 0.28</td>
<td>&lt; 0.36</td>
<td>&lt; 0.67</td>
<td>&lt; 1.30</td>
<td></td>
</tr>
</tbody>
</table>


$^d$ Observations from Ouchi et al. (2013). $^e$ In $\Delta \nu = 50$ km s$^{-1}$ channels.
IR-mm SED of « normal » z>6 galaxies from IRAM and ALMA

Boone et al. (2007):
- SEDs of Arp220, M82-like objects excluded
- SED compatible with nearby spirals or dwarf galaxies

Ota et al. (2014):
SED compatible with nearby irregulars or dwarf galaxies
IRX-beta relation of « normal » z>6 galaxies from IRAM and ALMA

IRX-beta relation compatible with nearby starbursts
Mean attenuation as function of redshift

**Dust-obscured SF:**

\[
\frac{\text{SFR(IR)}}{\text{SFR(UV)}}
\]

- (higher) attenuation from SED fits
- extrapolation of IR/UV results from \(z<3.5\)

**Burgarella et al. (2014)**

**UV attenuation compatible with:**

- attenuation from SED fits
- extrapolation of IR/UV results from \(z<3.5\)

**Schaerer et al. (2014)**
Mass – dust attenuation relation

- ≥ 2 objects: less attenuation than expected from relation at lower redshift

- Compatible with flatter mean relation for z~7 LBGs
  (Schaerer & de Barros 2014)
Dust masses of « normal » $z>6$ galaxies with IRAM and ALMA

Dust masses at $z>6$:

- Current upper limits are compatible with normal dust/stellar mass ratios.
- No indication for redshift evolution of $M_d/M^*$ from $z\sim0$ to 3 and at $z\sim7$.
- Dust production per SN $\sim0.15-0.45\ M_\odot$ (Hirashita+ 2014).

Schaerer et al. (2014)
Dust masses of « normal » z>6 galaxies with IRAM and ALMA

**Dust masses at z>6 :**

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- No indication for redshift evolution of M_d/M*

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**Figure:**

- **Graph:**
  - M_d/M* vs. redshift
  - Data points and error bars at various redshifts (z=0, 1, 2, etc.)
  - Universal and broken FMR curves
  - SFR and stellar mass plots

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**Citation:**
- Tan et al. (2014)
- Yajima et al. (2014)
[CII] emission from « normal » z>6 galaxies with IRAM and ALMA

- [CII] not detected (so far) in z>6 galaxies
- L([CII]) below local correlation with SFR (de Looze et al. 2012, 2014)
- Explanation for weak [CII] emission debated (Stacey+2010, Vallini+2013, Garcia-Lopez+ 2013, ...)

Ota et al. (2014)

Schaeer et al. (2014)
Current inferences from LBGs are not incompatible with latest mm observations!

Schaerer & de Barros (2014)

Implications

Stellar mass density

Ilbert et al. (2013)

Star formation rate density

Tacchella et al. (2013)

UV attenuation

Burgarella et al. (2013)

from UV slope
Implications

Analysis of large LBG sample with SED models allowing for:
- nebular emission
- variable SF histories

→ sSFR rising with redshift
→ Large scatter expected

de Barros et al. (2014)
Smit et al. (2014)

**Implications**

- Rising SF histories excluded for Himiko
- Poor constraint on sSFR
- Abell 1703-zD1: high sSFR $\sim 20-90$ Gyr$^{-1}$

→ More statistics needed!
SF galaxies @ z~6.5-7.5: conclusions

- New deep IRAM PdBI 1.2mm observations of two z=7 and 7.5 LBGs + 3 Lyman-alpha emitters at z=6.5-7 previously observed (IRAM + ALMA)
- [CII] + dust continuum undetected → limits on dust mass, IR luminosity, UV attenuation, dust-obscured SF
- SED compatible with nearby spirals, irregulars or dwarfs; not M82-like
- IRX-beta relation: objects compatible with local relation
- Limits on UV attenuation compatible with UV slope and SED fits
  - UV attenuation versus redshift:
    - OK with extrapolation from z<3.5 (Burgarella et al. 2013)
    - Can be higher by factor 2 estimated from UV slope
- Attenuation – stellar mass: probably flatter at z~7
- Dust/stellar mass ratio: universal. No evidence (yet) for difference with z~0-3
- High sSFR~20-90 Gyr^{-1} confirmed for 1 object

→ More deep IR-mm observations needed: ALMA, …