Determining the Stellar Ages of the First Galaxies

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with

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11th Sept. 2019, Extremely Big Eyes on the Early Universe, Rome
Searching for the first galaxies...

1. When did the first stars and galaxies form?

2. How many galaxies are there at a given luminosity?

3. Do galaxies emit enough ionising photons?

Searching for the first galaxies…

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1. When did the first stars and galaxies form?
2. How many galaxies are there at a given luminosity?


The dropout technique has given us hundreds of candidates at z>6 with which to characterise the Reionisation Epoch.

see also: Salmon+2018, Roberts-Borsani+2015
An alternative approach...

At high-z, Spitzer/IRAC bands probe the rest-frame optical. Strong nebular emissions lines (Hα, [OIII] 5007 Å and Hβ) can pollute the bands to produce a well-defined 3.6-4.5 μm vs redshift relation.

see also: Labbé+2013, Smit+2015
Spectroscopic galaxies at $z=7-9$
with red IRAC colours

IRAC excess due to older stellar populations: MACSJ1149-JD1

F435W   F606W   F814W   F105W   F125W   F140W   F160W   IRAC 1   IRAC 2

Zheng+2012,2017

- A bright, strongly amplified galaxy from CLASH/Frontier Fields with H$_{160} \sim$25 AB.
- Spectroscopic observations with ALMA ([OIII] 88μm) and VLT/X-Shooter (Lyman-α) place the galaxy at z=9.11.
- SED modelling and secure redshift suggest the IRAC-excess is due to a Balmer-break cause by older stellar population formed at z~15.

VLT/X-SHOOTER + ALMA/BAND 7

Hashimoto+2018

see Nicolas Laporte’s talk!
Is nebular emission the sole cause of IRAC-excess at $z>7$?

Spitzer/IRAC [3.6] and [4.5] micron bands boosted by different parts of the rest-frame optical spectrum: strong nebular emission lines or Balmer breaks?

see also: Labbé+2013, Smit+2015, Roberts-Borsani+2015
Can old stars reproduce Spitzer/IRAC colours?

Luckily, we have spectroscopically-confirmed galaxies with IRAC-excesses due to both nebular line emission (EGSY8p7; Roberts-Borsani+2015, Zitrin+2015) and a Balmer break (JD1; Hashimoto+2018) to test this picture.
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To explore this, we need SED models of various ages that self-consistently incorporate the evolution of stars, gas and metals, nebular emission, and dust production, over a large wavelength range (UV -> FIR/sub-mm). Introducing Pégase3.

- **Stellar evolution**: 
  - SSP models
  - Initial mass function
  - Stellar yields

- **Dust production**: 
  - Wavelength-dependent
  - Size distribution and optical properties of individual dust grains
  - Silicate + carbonaceous grains included
  - Projection effects included

- **Wavelength coverage**: 
  - UV to FIR/sub-mm

- **Nebular emission**: 
  - Initial metallicity of ISM gas (cooling)
  - CLOUDY
  - Emission of Lyman continuum photons
  - Includes dust obscuration

For more details see Fioc et al. (2019).
Can old stars reproduce Spitzer/IRAC colours?

- Looking at the colour evolution of an intense line emitter and Balmer break galaxy (masked lines).

- Assuming simple Pégase3 models with a Chabrier+2003 IMF, constant SFR, dust and different ages.

- Stellar ages of ~300-600 Myrs can reproduce IRAC colours at $z > \sim 8$. Thus, the explanation of nebular emission lines as the main/sole source of boosting is perhaps not universal.

- **IMPORTANT**: This does not imply one or the other, likely to be a mixture of both!

Roberts-Borsani, Ellis, Laporte (in prep.)
Are older stellar populations prevalent?

Is JD1 an isolated case or are there either known galaxies with evolved stellar populations?

- A handful of candidates from photometry and SED fitting…
  - Oesch+2014
  - Tamura+2018

- 3 high-z massive galaxies in a 50 Mpc (comoving) box…
  - Bouwens+2019
  - Katz+2018
How do we distinguish at z=7-9?

We need JWST and EXTREMELY BIG EYES!!!

<table>
<thead>
<tr>
<th>Telescope/Instrument</th>
<th>Wavelength coverage (μm)</th>
<th>Spectral Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMT/NIRES</td>
<td>1-5</td>
<td>R~100,000</td>
</tr>
<tr>
<td>ELT/METIS</td>
<td>2.9-14</td>
<td>R~900-100,000</td>
</tr>
<tr>
<td>JWST/NIRSpec</td>
<td>0.6-5.3</td>
<td>R~1,000-2,700</td>
</tr>
</tbody>
</table>

Such observations crucial to determine accurate stellar masses, stellar ages, and constraining the timing of Cosmic Dawn!
Summary & Conclusions

1. The rest-frame optical provides important information on the stellar populations, ionising conditions and gas of galaxies. At high-z this is probed by Spitzer/IRAC channels.

2. The discovery and modelling of JD1 has placed the universality of emission lines as the main cause of red [3.6]-[4.5] colours in doubt.

3. Spectroscopic data sets and Pégase3 SEDs suggest IRAC colours can be explained by older stellar populations too. Implications for galaxy ages and timing of Cosmic Dawn.

The arrival of 30m-class telescopes and JWST will aid to distinguish between the two scenarios and help constrain the timing of Cosmic Dawn.