Star forming galaxies at z>6 and beyond

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• Introduction
  – Motivation
  – What and how?

• Data set (old and new)

• Results
  – limitations and errors
  – Comparisons with others
Motivation

• Constraining the abundance of starforming galaxies at z~6-10

  – better understanding of first generation of stars and galaxies (Loeb & Barkana 2001, Saas Fee 2006)
  – new models of low metallicity starbursts (Schaerer 2002, 2003)

  – observational properties derived from these tell us, that it is now possible to detect some of these first objects up to z=8-10

Bouwens et al. 2005
...you look for

- Lyman break galaxies or Lyα-emitters,
- SCUBA sources
- passive evolving galaxies

...by looking at

- and you do it either in deep fields, fields of gravitational lenses, or spectroscopic surveys
Data

• 2 lensing clusters
  – AC114: known gravitational lens
  – Abell 1835: most X-ray luminous cluster in X-ray Brightest Abell-type cluster catalog

• NIR: ISAAC (SZ)JHK data (H-band for first detection)
  Optical: FORS, CFHT, HST/WFPC2
Models

- Starburst models for metal-deficient galaxies (Schaerer 2001, 2003)
- Bruzual & Charlot 1993
- SB templates by Kinney et al. 1996
- Top-heavy or Salpeter IMF

- optical dropouts + near-IR colours
- extending the drop-out technique to \( z > 7 \)

Filter combinations:
- \( z \sim 6-7 \): \( zSZJ \)
- \( z \sim 7-8 \): \( SZJH \)
- \( z > 8 \): \( JHK \)
• 9+7 high-z candidates in Abell 1835 and AC114

A1835 (z>6)

A1835 (z>7)

A1835 (z>8)

AC114 (z>8)
Corrections applied to these data

- **Lensing:**
  1) gravitational magnification
  2) reduction of the effective surface by the same factor (dilution).

- Photometric incompleteness

- & false positive detections (depending on the detection filters)
• LF integrated down to 0.3 L*{z=3}
• Results fairly compatible with previous findings at z<6, but up to a factor ~10 higher than present z~6-10 studies (UDF, (Bouwens et al. 2004-2006).

• discrepancies with other determinations in blank fields. Some possible explanations:

• **Sample variance:** strong field-to-field variance expected in small fields. Already seen between A1835 and AC114!

• Positive magnification bias in our sample due to mid-z interlopers.

• Residual contamination by fake detections
Intrinsic properties of high-z candidates

• Typical magnification of our candidates: 1.5 to 10 (~0.4 to 2.5 mag).
  Average(median) magnification of 1st-priority candidates:
  6.5 (2.3) in Abell 1835 and 7.9 (3.5) in AG114.

• *All high-z candidates* turn out to be *fainter* than H = 23.0 (AB ~ 24.5)
  -- although magnitude NOT a selection criterion
  → After correction for magnification, the lack of ”bright” sources means that we
  have not detected young starbursts at z~6-10 more massive than typically a few
  10^8 M_solar (standard IMF).

• From L_1500: SFR ranging between a few units and 20 M_solar/yr
  But assumed equilibrium condition and/or standard conversion not necessarily
  reached in these objects!

• Also: Very blue UV slope (β~ -1.5 to -3.5) cf. GOODS, UDF… surveys
  ==> Indication for little or no extinction!?
• Targets: 2 priority candidates in AC114, and 7 in Abell 1835
• Sample of 9 targets, 2/3 of the objects observed display emission lines.
• A large majority of our high-z candidates still need to be (re)confirmed by redetection of a faint emission line, or by non-detection of other lines expected at low-z.

\[ z = 7.17 \text{ candidate if Ly-}\alpha \]
\[ z = 7.89 \text{ candidate if Ly-}\alpha \]
\[ z = 1.89, \text{ doublet of [OII]3727} \]
\[ z = 1.67, \text{ 3 lines detected (Richard et al. 2003)} \]
Multi-colour follow-up

- ACS/HST z-band observations (non-detection $Z_{AB}>28.3$) confirm «dropout» nature of $z>~7$ candidates behind A1835 and AC114

- IRAC/Spitzer: high-z candidates not detected -->
  As expected: compatible with SED of young starburst

- IRAC/Spitzer: detects brightest objects (ERO) between 3.8 and 8 µm --> new constraints on their nature and redshift

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ACS, NIR and Spitzer

- Lensed high-z candidates:
  - 11 objects remain undetected at 3.6 and 4.5 micron in median stacked images
  - 2 sigma upper limit per source is 0.16 to 0.2 \(\mu\)Jy at 3.6-4.5 micron
  - except for 1 object upper limits are compatible with the expectations from extrapolating their SED to longer wavelengths!

- IRAC non-detection can be understood if objects are young star forming (blue) galaxies at high-z!
Problem

- EROs with optical non-detection: degenerated best-fit solution at low- and high z

- SEDs similar to those of high-z objects
• **Red optical drop-out objects:**
  - e.g. a massive post-starburst galaxy at z~6.5 !? (Mobasher et al. 2005)

• SED fit degenerate (z~2.5 or ~6.5-7.5) as for our EROs
  - $\chi^2$ similar at low/high-z if minimum error $\sim$0.1-0.15 mag
  - detected in V,l, z ? (Dunlop et al. 2006)

• Good SED fit semi-empirical ERO template found at z~2.4 --> accounts naturally for observed 24 $\mu$m flux!
Summary

- Deep near-IR study of strong lensing clusters has provided sample of 18 high-z galaxy candidates and sample of optical drop-out EROs (Richard et al. 2006)
- \( \Rightarrow \) no strong drop of SFR density from z~6 to 10

- HST/ACS follow-up: confirms 17 as optical (z-band) drop-out
- Spitzer/IRAC: 11 objects uncontaminated
- high-z candidates undetected
- for 10/11: IRAC non-detection understood if objects are young star forming (blue) galaxies at high-z
- lensed galaxies: Spectroscopic follow-up feasible with ground-based near-IR MOS

- Optical drop-out EROs: similar SEDs as IRAC selected EROs (Yan et al. 2004) and GOODS z~6.5 post-starburst candidate (Mobasher et al. 2005)
- SED fit degenerate low-z / high-z (z~1.5-3 or ~6-8!?)
- Low-z solutions more likely
What about 1916?

- **ISAAC**: Feb. 2003

- **Gemini**: May 2004
  M.N. Bremer et al. 2004, 615, L1-L4

- **NICMOS**: July 2005
**New photometry → INTRINSIC VARIABILITY OF THE SOURCE: AGN?**

Non-detection in H (29/06/04; Bremer et al 2004)
Re-detection at 1.06 microns (05/04) → more likely z~7-8.
Non-detection on deep images in the visible bands (Keck & VLT; e.g. Lehnert et al. 2005) → confirmation as « optical dropout »)

**New spectroscopy in the H band: low-z solutions excluded/unlikely**
- 1.6915 to 1.8196 microns, 2 adjacent bands (30/36 frames x 900 sec).
- no other lines detected (e.g. HeII 1640 …)
- all solutions at low-z between z~2 - 2.6 seem excluded, as well as most solutions at z<2.

**Re-analysis of original ISAAC spectra:**
Absolute wavelength calibration was ~4.5Å off (=>7-9 pixels in blue-red bands)
in original paper: line detected at 1.33790 (+/- 0.0001) microns (instead of the 1.33745 microns). Photometric constraints: more likely CIV1550 → z = 7.6.
Joint detection in H, K, SZ, and emission line → probability of spurious detection very low!
• **Lensed optical drop-out EROs from Richard et al. (2006):**
• 5 EROs detected by Spitzer (3 contaminated)
• similar to IRAC selected EROs from HUDF (Yan et al. 2004)
• photometric redshifts degenerate for most objects
• IRAC/Spitzer helps lifting degeneracy (not always)
• High-z (z~6-8) solution unlikely: very/too bright objects!

• Spitzer + sub-mm (IRAM/APEX/…) sheds new light on nature of faint red optical drop-out and very dusty intermediate z galaxies

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▪ Lensing clusters are expected to be a factor of 5-10 more efficient than blank fields in the 7<z<11 domain

▪ Standard Salpeter IMF and simple assumptions are ~OK at 6<z<8. An excess of counts is observed at z>8, but these are only CANDIDATES!
LF fit with
\( \alpha = -1.6 \) fixed (as for LBGs \( z \sim 3-4 \) (Steidel et al. 99):

- compatible with Steidel’s LF (\( z \sim 4 \)) without any renormalization
- the turnover observed by Bouwens et al. (2005) in the UDF, towards the bright end of the LF is not observed in this sample.