Highlights from HiZELS
The High Redshift (Z) Emission Line Survey

David Sobral
Leiden Observatory

Philip Best, Ian Smail, Jim Geach, Michele Cirasuolo, Mark Swinbank, Yuichi Matsuda, Jaron Kurk, Rob Ivison, Mark Casali
Star formation Activity

- Combining all tracers doesn’t really help...
- Dust dependence + selection biases + sensitivity + etc.

Huge scatter! >0.5 dex
Critical era => important to constrain!
Hopkins 2004
Stellar Mass Assembly

- Stellar Mass function
- Ilbert et al. 2010
- Stellar mass density evolution
- Marchesini et al. 2009
Combining both...

- Selection effects?
- Completeness?
- IMF?  •  Missing Mass?

- Hopkins & Beacom 2006
- Different tracers? Biases?

- Hopkins 2004
How can we improve our Understanding?

- A good (single) star-formation tracer that can be applied from $z=0$ up to $z\sim3$ (with current instrum.)
- Well calibrated and sufficiently sensitive
- Able to \textit{uniformly} select large samples
- \textbf{Different epochs}
- \textbf{Large areas}
- \textbf{Best-studied fields}
**Ha (+NB)**

- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **Narrow-band technique**
- Now with WFCAM: over large areas
  - And traced up to $z \sim 3$
HiZELS

The High Redshift Emission Line Survey

- Deep & Panoramic extragalactic survey, narrow-band imaging (NB921, NB_J, NB_H, NB_K) over ~ 5 deg^2 (UKIDSS DXS fields)

  (+Deep NBH + Subar-HiZELS + HAWK-I)

- Narrow-band Filters target H\(\alpha\) at \(z=0.4, 0.84, 1.47, 2.23\)

- Same reduction+analysis

- Other lines (simultaneously; Sobral+09a,b,Sobral+12a)

- UKIRT + VLT + Subaru
Including data taken 1-2 months ago
All sources K band => Line emitters NBK
Line emitters NBK
H-alpha sources: Double/triple NB + photo-zs + colours
Clean, complete “slices” of 1000s of H-alpha selected galaxies in the last 11 Gyrs
Double-NB survey
Sobral+12a
400 Hα+[OII] / night!
Subaru joins UKIRT to “walk through the desert”
The first Hα-[OII] large double-blind survey at high-z
Sobral et al. 2012a, NAOJ press release

without any need for colour or photometric redshift selections
\( z = 2.23 \): \( \text{H}\alpha \) (NBK), \([\text{OIII}]\) (NBH), \([\text{OII}]\) (NBJ)

\( z = 1.47 \): \( \text{H}\alpha \) (NBH), \( \text{H}\beta \) (NBJ), \([\text{OII}]\) (NB921)

\( z = 0.84 \): \( \text{H}\alpha \) (NBJ), \([\text{OIII}]\) (NB921)
### HiZELS: Progress

~95% complete

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<th>Time</th>
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<tr>
<td>27 hrs</td>
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Each field = 0.8 deg$^2$ (4xWFCAM)

**Depths:** (NB921~26), NBJ~22.8, NBH~22.6, NBK~22.9 (AB)

**Line Flux limit:** $\sim 0.5-1.0 \times 10^{-16}$ erg s$^{-1}$ cm$^{-2}$
H-alpha emitters in HiZELS

2 sq deg: COSMOS + UDS

z=0.4: 1742  z=0.8: 637  z=1.47: 515 and z=2.23: 630

In ~1 yr: Full HiZELS (UKIDSS DXS fields) + CFHT (SA22):

z=0.8: 3500  z=1.47: 1200 and z=2.23: 1500

along with 1000s of other z~0.1-9 emission line
selected galaxies
Faint-end Slope $\alpha$: 

Up to $z=2.2$: 

$$\alpha = -1.60 \pm 0.08$$

$L^*$; “Break” of the LF

Typical SFR ($\text{SFR}^*$) is changing significantly with time!

Up to $z=2.2$:

$$\log L^*(z) = 0.45z + \log L^*_{z=0}$$

$$\log \text{SFR}^* = 0.45z + \log \text{SFR}^*(z=0)$$
HiZELS => Dark Energy missions forecast

Hirata et al. 2012
Salpeter IMF
\[
\log \rho_{SFR} = -2.1/(z + 1)
\]
\[ \log \rho_{\text{SFR}} = -0.14T - 0.23 \]

\[ \log \rho_{\text{SFR}} = -2.1/(z + 1) \]
95% SMD formed since $z=2.2$

Sobral+12b, arXiv:1202.3436

\[
\log \rho_{\text{SFR}} = -0.14T - 0.23
\]
95% SMD formed since $z=2.2$

Universe will only gain 5% more stellar mass density

$\log \rho_\text{SFR} = -0.14T - 0.23$

Sobral+12b, arXiv:1202.3436
- Robust measurement of the Evolution of the Hα LF over 11 Gyrs and fully self-consistent (Hα) star-formation history \( z < 2.3 \).
- 1742, 637,507, 630 Hα emitters at \( z = 0.4, 0.8, 1.5, 2.2 \); factor of \( \sim 10 \) times larger than previous samples
- Evolution in Hα LF:
  
  \[
  \log L^*(z) = 0.45z + \log L^*_{z=0}
  \]
  
  \[
  \alpha = -1.60 \pm 0.08
  \]
- SF History of the Universe:
  
  \[
  \log \rho_{\text{SFR}} = -0.14T - 0.23
  \]
  
  \[
  \log \rho_{\text{SFR}} = -2.1/(z + 1)
  \]
- Agreement with stellar mass density growth suggests that the Hα analysis is tracing the bulk of star formation since \( z \sim 2.2 \)

**Highlights**

2009-2012

Using the clean, SF selected samples to understand galaxy evolution
The role of the Environment

- A very wide range of environments - from the fields to a super-cluster (Sobral et al. 2011)
  - X-rays

- 10th nearest neighbour density maps

- UKIDSS UDS z=0.84
- COSMOS z=0.84
The role of the Environment

- Use high quality photo-zs to estimate distance to 10th nearest neighbour >> use spect-z to estimate completeness and contamination >> compute corrected local densities

“Calibrate” environments in a reliable way using the accurate clustering analysis and real-space correlation lengths of field, groups and clusters

Sobral et al. 2011
Environment sets the faint-end slope of the H\(\alpha\) LF:

- **steep** \(\alpha \sim -2\) for the lowest densities

- **shallow** \(\alpha \sim -1\) for highest densities
The fraction of (non-merging) star-forming galaxies declines with both mass and environment. Mass and Environment

Sobral et al. 2011

Fig 6: The red fraction in SDSS as functions of stellar mass and environment.

with the values $p_1$ to $p_4$ given in Table 2, plotted at intervals of 0.2 dex in $m$ and $\delta$.

The separation of the effects of mass and environment is naturally not perfect but holds over two orders of magnitude in both mass and environmental density, with local deviations from the horizontal lines that are comparable to the observational uncertainties. The limited excursions of the data show that deviations from this simple separable behavior in $m$ and $\delta$ are rather small, equivalent to no more than $r_0.2$ dex in either variable, a tenth or less of the overall range of each parameter.

In other words, the differential effect of the environment on the red-blue mix of galaxies in SDSS is independent of galactic stellar mass, and vice versa. This good empirical separability of mass and environment means that we can write the red fraction in terms of $F_{\text{red}}(\delta, m)$ and $F_{\text{red}}(m, \delta)$, by either of the first two equations, which reduce to the third:

$$f_{\text{red}}(\delta, m) = \frac{1}{p_1 + \frac{m}{p_3} + \frac{\delta}{p_4}}$$

with $p_{\text{red}}$ independent of $\delta$ and with $p_{\text{red}}$ independent of $m$.

This implies a simple symmetry to the $f_{\text{red}}(\delta, m)$ surface, which is illustrated in Fig 6.

Since $p_{\text{red}}$ is zero in the lowest density regions (i.e. the voids), this separability means that $p_{m}(\delta)$ is easily interpreted as the red fraction in these lowest density regions. Likewise, $p_{\delta}(\delta)$ is the red fraction for very low mass galaxies, for which $p_{m}$ is by construction zero.

By inserting the two fitted relations (5) into (6), we recover

$$f_{\text{red}}(\delta, m) = \frac{1}{p_1 + \frac{m}{p_3} + \frac{\delta}{p_4}}$$

which was previously proposed by Baldry et al. (2006) as one of two empirical fitting functions for the $f_{\text{red}}(\delta, m)$ surface in SDSS.

The clear separability of the effects of environment and mass, when parameterized in this way, suggests that there are two distinct processes at work. We will henceforth refer to these as "environment-quenching" and "mass-quenching" to reflect their (independent) effects on $f_{\text{red}}$ across the $(\delta, m)$ plane. These two quenching processes will be governed by rates (i.e. the probability of being quenched per galaxy per unit time) of $\gamma_{\delta}$ and $\gamma_{m}$ respectively.

The distinction between the two effects will be even more clearly seen when we consider how, observationally, $p_{\text{red}}$ and $p_{\text{red}}$ depend on cosmic epoch. For this we turn to our zCOSMOS sample in the next Section.

4.3 How the environment-quenching operates

4.3.1 The empirical signature of environment-quenching

Fig 7 shows the equivalent plots of $p_{\text{red}}$ and $p_{\text{red}}$ from the $f_{\text{red}}(\delta, m)$ surface in SDSS (Peng+10) z~0 Mass trend at least up to z~1.5

Mass trend at least up to z~1.5

The fraction of (non-merging) star-forming galaxies declines with both mass and environment

SDSS (Peng+10)
The Environment at $z \sim 1$

Can we reconcile the apparent contradictions?

- Field Studies
- Cluster+outskirts
- Rich Clusters

(e.g. Elbaz+07, Ideue+09)
Koyama+10

(e.g. Patel+09; EDisCS
Poggianti+05,09)

Star-forming Fraction
Local Projected Density

Star-formation rate
Local Projected Density
Environment at $z \sim 1$

Results reconcile previous apparent contradictions
Extinction-Mass z~0-1.5

Stellar Mass correlates with dust extinction like in the local Universe - (agrees with Garn & Best 2010)

Simpler way to predict dust extinction with observables: optical/UV colours - empirical relations valid at z~0-1.5 (Sobral et al. 2012a)
Dust extinction-SFR in the last 9 Gyrs

Does the empirical SFR-dust extinction dependence hold at z~1.5?

No! Offset of ~0.5 mag

Local relations (extinction corrections as a function of observed luminosity) over-predict dust-corrections at high redshift

Sobral et al. (2012a)
Dust extinction-SFR in the last 9 Gyrs

Does the empirical SFR-dust extinction dependence hold at z~1.5? and if we take into account the luminosity evolution?

\[ \log[L^*(z)] \propto 0.5z \]
Dust extinction-SFR in the last 9 Gyrs

Does the empirical SFR-dust extinction dependence hold at $z \sim 1.5$?

Yes, if we account for the luminosity/L*(z) evolution

~Same population(!?), just overall more luminous

So (apart from the L* evolution) ~no evolution(?) in dust extinction of star forming galaxies

$$\log[L^*(z)] \propto 0.5z$$
Dust extinction-SFR in the last 9 Gyrs

Does the empirical SFR-dust extinction dependence hold at \( z \sim 1.5 \)?

Yes, if we account for the luminosity/L*(z) evolution

“Fixed luminosity”? 

\[ \log[L*(z)] \propto 0.5z \]

So “fixed” ULIRG/LIRG class/ make no sense; but ULIRG(z) / LIRG(z) classifications might

(at \( z \sim 2 \), ULIRGs \( >10^{13}L_\odot \) LIRGs \( >10^{12}L_\odot \))
Clustering

Geach+12

Sobral et al. 2010

$z=0.8$

$z=2.23$
Clustering of Hα at z~1

Clustering depends on Hα luminosity; galaxies with higher SFRs are more clustered

Sobral et al. 2010

z=0.84
Clustering of Hα emitters

Clustering depends on Hα luminosity; galaxies with higher SFRs are more clustered

Clustering-Hα relations at 3 very different epochs...

Same DM Halo mass: much more efficient at High-z

Sobral et al. 2010
Using the Luminosity evolution (L*) measured before...

Scaling Hα luminosities by the break of the Hα luminosity function recovers a single relation, independent of time across the bulk of the age of the Universe.
Accounting for evolution of the typical SFR (SFR* or L*):

\[ \log L^*(z) = 0.45z + \log L^*_z=0 \]

~No evolution in number density of SFGs over last 11 Gyrs
A simple view: 11 Gyrs of SFGs with HiZELS

- Strong Evolution: Typical SFR (SFR*) reduces by 1/10
- Many statistical properties remain “unchanged”: Dust “extinction”, Mass function (M*,alpha)
- Environmental + Mass trends are the same (last ~9 Gyrs)
- Same Dark Matter halo masses host the same L/L* galaxies
Summary:

- Evolution of the Hα LF over 11 Gyrs and fully self-consistent (Hα) star-formation history z<2.3.
- Hα emitters at z=0.4-2.2; factor of ~10 times larger than previous samples
- Evolution in Hα LF: \( \log L^*(z) = 0.45z + \log L^*_{z=0} \) \( \alpha = -1.60 \pm 0.08 \)
- SFH of the Universe: \( \log \rho_{\text{SFR}} = -2.1/(z + 1) \) \( \log \rho_{\text{SFR}} = -0.14T - 0.23 \)
- Agreement with stellar mass density growth
- Dust extinction in SF galaxies 9 Gyrs ago ~similar to SDSS
- z~0 mass and environment dependences already there up to z~1.5
- Single L*(z)-DM halo connection up to z~2.2 and L* scaling: important insight?
Fraction of AGN within the sample

UKIDSS DXS Fields!

Sobral et al. 2012c
The nature and evolution of luminous line emission.

- **Hα Luminosity**
  - More Metal-rich
  - More Metal-poor
  - Star-forming

**Broad-line AGN**

**AGN dominated**

**AGN + SF**

Dynamics & Metallicity gradients H-alpha $z=0.8, 1.47, 2.23$

Swinbank et al. 2012
Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012

From AO IFU observations
Metallicity gradients H-alpha $z=0.8, 1.47, 2.23$
Don’t believe [OII]/Ha?

Ha emitters are “typical” SF galaxies at their epoch luminosities of z=0 LIRGs

Ha AGNs: hotter & more luminous in FIR

Let’s look at the MIR/FIR w/ Herschel

Ibar, Sobral, Ivison et al. 2012
Dust corrections as a function of observed H-alpha would get it completely wrong!

Dust Corrections as a function of Mass work the best

FIR derived $A_{\text{Ha}} = 0.9-1.2$ mag
~Same as $\text{[OII]}/\text{Ha}$

Garn & Best (2010) (Balmer dec.)
Sobral et al. (2012a) (using $\text{[OII]}/\text{Ha}$)

Ibar, Sobral, Ivison et al. 2012
Ha luminosity function z>1?

Samples still too small: <50 sources

L* Evolution: but by how much?

$z \sim 2$

Faint-end slope?
Hayes et al: $\alpha = -1.7$
Tadaki et al: $\alpha = -1.3$

Is $\alpha$ getting steeper with $z$?

Ha LF $z \sim 2$; Tadaki et al. 2011
Ha luminosity function $z \sim 1$?

Samples now ~ large enough but:

- Each study focus on a ~single redshift and uses:
  - Different Selection criteria
  - Different apertures
  - Different areas + depths

So they can disagree even at the same redshift

Evolution vs methods?

e.g. $z \sim 0.8$  Ly et al. 2011
The nature and evolution of luminous line emission in high-redshift AGNs and star-forming galaxies. 

### Broad-line AGN

- **AGN dominated**
- More Metal-rich
- More Metal-poor
- Star-forming

### AGN + SF

- Wavelength (μm)

### Hα Luminosity

- z=1.47
\( \Sigma > 3, \text{EW}_{(\text{Ha}+[\text{NII}])} > 25 \, \text{Å} \)

\begin{align*}
\text{Limit SFR} & \quad \text{Volumes (UDS + COSMOS)} \\
0.01 & \quad \sim 1 \times 10^5 \, \text{Mpc}^3 \\
1.5 & \quad \sim 2 \times 10^5 \, \text{Mpc}^3 \\
3.0 & \quad \sim 8 \times 10^5 \, \text{Mpc}^3 \\
3.5 & \quad \sim 7 \times 10^5 \, \text{Mpc}^3
\end{align*}

\( z = 0.4 - 2.23 \)

\begin{tabular}{|c|c|c|c|c|}
\hline
\text{NB filter} & \text{\( \lambda_c \) (\text{\( \mu \text{m} \))} & \text{FWHM (\text{Å})} & \text{\( z \, \text{H}_\alpha \)} & \text{Volume (\text{H}_\alpha) (10^4 \, \text{Mpc}^3 \, \text{deg}^{-2})} \\
\hline
\text{NB921} & 0.9196 & 132 & 0.401\pm0.010 & 5.13 \\
\text{NB}_J & 1.211 & 150 & 0.845\pm0.015 & 14.65 \\
\text{NB}_H & 1.617 & 211 & 1.466\pm0.016 & 33.96 \\
\text{NB}_K & 2.121 & 210 & 2.231\pm0.016 & 38.31 \\
\text{HAWK-I H}_2 & 2.125 & 300 & 2.237\pm0.023 & 54.70 \\
\hline
\end{tabular}
Klypin, Trujillo-Gomez, & Primack 2011
So is it just “nature”/mass? Or is the environment important as well?

Local Universe: star formation activity declines with increasing environmental density

How important is the local environment? Does the role change with redshift?

Cooper et al. 2007
The Ha + [OII] view

- Detailed evolution of the Ha LF: strong $L^*$ evolution to $z \sim 2.3$

**Sobral+11b**

First self-consistent measurement of evolution up to $z \sim 2.3$

Strong evolution can also be seen using fully consistent measurements of the [OII] luminosity function up to $z \sim 1.8$
Strategy:

z=6.6: Subaru: NB921 wide survey (already awarded time as PI + proposed to cover total of ~5 sq. deg.)

z=7.1: VISTA (LASER) - deep + “Ultra-wide” (10 sq. deg) Co-I

z=8.8: VISTA “Ultra-wide” ~10 sq proposed as PI + ELVIS UltraVISTA