Measuring oxygen abundance with Subaru-MOIRCS et al.
Preliminary results of 4 near-infrared spectroscopy programs with VLT and Subaru of zCOSMOS galaxies at 0.5<z<1 and 2<z<2.5 (PI: C. Maier, ETH Zurich, zCOSMOS data manager):

• SUBARU-MOIRCS: 4 half nights in January 2010
• VLT-SINFONI: 37 hours observed Jan – April 2010
• VLT-ISAAC P84: 23.5 hours observed Jan – March 2010
• VLT-ISAAC P85: 23.5 hours: observations started in Apr 2010
Near-Infrared spectroscopy with ISAAC of zCOSMOS galaxies at 0.5<z<1

- VLT-ISAAC P84: 23.5 hours Jan – March 2010
- VLT-ISAAC P85: observations started in Apr 2010
- SUBARU-MOIRCS: 5 proposed nights for Jan 2011

Aim: measure Hα and [NII] in 100 zCOSMOS galaxies
- to measure reliable metallicities, which also allows:
  - to measure SFRs from extinction corrected Hα
  - to identify Type-2 AGNs using the BPT diagram
  - to study environment effects (e.g. groups vs. field) on SFRs, metallicities etc.
[O/H]-abundance using the $R_{23}$ method

\[ R_{23} = \frac{[\text{OIII}]\lambda5007,4959 + [\text{OII}]\lambda3727}{H\beta} \]

- $R_{23}$ method was introduced by Pagel et al. (1979)
- $R_{23}$ must be corrected for reddening and degeneracy

must be broken using the

[NII]λ6584/Hα ratio
[O/H] vs. mass relation of galaxies without near-IR follow-up

(only zCOSMOS VIMOS spectroscopy for [OII], Hβ and [OIII])

- Panels a) and b): [O/H] abundances of zCOSMOS galaxies with 3 emission line measured, assuming $A_V=1$, and $\text{[NII]}/H\alpha<0.1$ (lower branch, panel a), $\text{[NII]}/H\alpha>0.1$ (upper branch, panel b)

- Panel c) shows that the assumption of the upper branch is wrong for a substantial fraction of galaxies of these masses based on near-IR follow-up of CFRS galaxies (Maier et al. 2005) → need for near-IR follow-up at $z>0.5$
ISAAC 2010 near-IR spectroscopy of zCOSMOS 0.5<z<1 galaxies: preliminary results

• SZ and J-band VLT-ISAAC spectroscopy to measure H\(\alpha\) and [NII] line fluxes for ~40 zCOSMOS galaxies at 0.5<z<1 with [OII], H\(\beta\), and [OIII] from VIMOS optical spectroscopy

• Exposure times: 30-60 min in SZ or J band, depending on the H\(\beta\) line strength measured with VIMOS (>4*10\(^{-17}\)ergs/s/cm\(^2\))

• The velocity accuracy of ~100km/s of the zCOSMOS spectra allowed us to check that both H\(\alpha\) and [NII] are not affected by strong OH lines (center of line further than 8Å away)

• X-ray AGNs excluded based on the COSMOS XMM (Brusa et al. 2007) and Chandra (Elvis et al. 2009) observations

• ISAAC-P84: candidates for low-metallicity galaxies to determine their number and physical nature: crucial for the mass-metallicity relation at intermediate redshifts

• ISAAC-P85: mass-complete sample to disentangle environment effects
Example spectra of zCOSMOS objects at $0.5<z<1$ with VLT-ISAAC NIR spectroscopy

$\text{H}\alpha$  $[\text{N}\text{II}]$
Comparison of SFR from 24μm (Paschen-α) and SFR from Hα

- one of the best-understood SFR indicators is Hα: the Hα extinction corrected luminosity is directly proportional to the hydrogen-ionizing radiation from massive stars
- SFR from IR (Emeric Le Floc’h):
  a) convert the rest-frame 8 μm luminosity to a dust-corrected Paschen-α luminosity using the calibration from Calzetti et al. (05) and Dias-Santos (09)
  b) convert this to SFR using a calibration from Osterbrock (1989)
The metallicity-mass relation using near-IR spectroscopy

- Reliable $[\text{O/H}]$ abundances of zCOSMOS $0.5 < z < 1$ galaxies using an $\chi^2$ analysis by simultaneously fitting the 5 emission lines in terms of $[\text{O/H}]$, extinction and ionization parameter, using the models of Kewley and Dopita (2002), as described in Maier et al. (2005)
Preliminary results with ISAAC 2010 data: **Size-metallicity relation**

- Half-light radius from GIM2D Sersic fits done by Sargent et al. (2007)
- Higher [O/H] in larger galaxies: to be confirmed with all ∼40 ISAAC observed galaxies
Near-Infrared spectroscopy with SINFONI and MOIRCS of zCOSMOS galaxies at 2.1<z<2.5

- SUBARU-MOIRCS: 4 half nights end of January 2010
- VLT-SINFONI: 37 hours observed Jan – April 2010

Aim: measure [OII] (J-band), Hβ and [OIII] (H-band) Hα and [NII] (K-band) in 2.1<z<2.5 zCOSMOS galaxies

- to measure reliable metallicities, which also allows:
- to measure SFRs from extinction corrected Hα
- to identify Type-2 AGNs using the BPT diagram
- to study environment effects (e.g. groups vs. field) on SFRs, metallicities etc.
Metallicities at 2<z<2.5

- The five lines required to use the $R_{23}$ method breaking the high/low branch degeneracy are $\text{[OII]}$ in J-band, $\text{H}\beta$ and $\text{[OIII]}$ in H-band, and $\text{[NII]}$ and $\text{H}\alpha$ in K-band.
- The chance of having all five lines clear of OH line is not so high, <50% as shown in the figure.
- Not one of the pioneering studies of metallicities at z>2 has measurements of all five lines, and only a handful have measurements of even four or three lines (four galaxies of Erb et al. 2006, five of Pettini & Pagel 2004, two LSD galaxies of Mannucci et al. 2009, and a couple AMAZE objects).
4 half nights Subaru-MOIRCS in January 2010

- MOIRCS (multi-object infrared camera and spectrograph) at Subaru: field of view of 4x7 square arcminutes
- resolution with 0.8 arcsec slit: $R \approx 950$ in $K$ ($\text{H}\alpha$ and $\text{[NII]}$ at $z \approx 2.3$), and $R \approx 1900$ in $J$ ($\text{[OII]}$) and $H$ ($\text{H}\beta$ and $\text{[OIII]}$) using new VPH-J and VPH-H grisms
4 half nights Subaru-MOIRCS in January 2010

- one mask MOIRCS (9-10 main targets + several additional targets) in 4 half nights (~6 hours exposure time in each K, H, and J)
- observations done under reasonable weather conditions, data are being reduced, but no official MOIRCS pipeline → I am using Yoshikawa pipeline (but description in Japanese, so progress slow)

- Additional issue: higher resolution VPH-J and VPH-H grisms: wavelength sensitivity dependent on position of object on the mask

→ difficult to find best pointing to maximize number of targets and optimize the wavelength sensitivity → I used two masks with slightly shifted object positions in J and H to optimize this for [OII] in J, Hβ and [OIII] in H

→ calibration with standard star more difficult: I had to observe a standard star at different position on the chip (corresponding to positions of targets) to account for the wavelength dependence of the VPH grisms: larger overhead of the observations, and data reduction more complicated
4 half nights Subaru-MOIRCS in January 2010

Preliminary reduction: example of z~2.2811 zCOSMOS galaxy


↔ zCOSMOS VIMOS spectrum

↔ ACS image
SINFONI non-AO program: JHK spectroscopy at z~2.3

- **37 hours SINFONI non-AO** in P84, observations January-April 2010 (just finished in April 2010): 40 min in K, 1h in H, 1h in J
- A dozen of zCOSMOS-Deep 2<z<2.5 galaxies, including 3 objects with K-band observations from SINFONI Large Program LP (PI: A. Renzini)
- Selection: SFR from COSMOS SED > 43Msun/yr → expected Hα flux >10*10^{-17} ergs/s/cm^2) + not expected to be affected by OH line
- However: zCOSMOS-Deep redshift accuracy ~300km/s, and absorption lines (UV with VIMOS) can show significant velocity offset with respect to emission line gas (e.g. seen in SINS, Forster-Schreiber et al. 2009)

→ iterative scheme: first measure Hα with SINFONI for 15 objects in K-band, then use the detection/non-detection + emission line redshift to select the best (handful of) SINFONI targets for which all 5 lines can be observed
VLT-SINFONI non-AO: examples of two zCOSMOS galaxies with 5 lines measured

$z=2.2450$ (upper panels) and $z=2.4579$ (lower panels)

|--------------|----|----------------|-----------|------|
Overview detections in Hα from SINFONI and MOIRCS

- SINFONI LP, SINFONI P84/85 metallicity program, MOIRCS galaxies with Hα detected (filled symbols) and Hα not-detected (open symbols)
- 12/15 SINFONI P84 galaxies detected in Hα, 8 MOIRCS galaxies detected in Hα
- Non-detections because of bad seeing, low surface brightness, wrong SFR from SED and/or OH lines
Overview detections in Hα from SINFONI and MOIRCS

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Oxygen abundance vs. stellar mass at $z \sim 2.3$

- Data reduction ongoing; 3 preliminary points from SINFONI $z \sim 2.3$
Metallicities at 2<z<2.5: anomalous line-ratios

- For 87 galaxies at 2<z<2.5, Erb et al. (2006) used the N2 method (based on the [NII]/Hα ratio) to estimate oxygen abundances, a controversial method plagued by uncertainties in reddening and ionization level, claimed to be unreliable by some authors (e.g. Shi et al. 2007)

- Only 4 of the 87 galaxies have [OIII] and Hβ line fluxes measured additional to [NII] and Hα

- These 4 galaxies lie in the region of the BPT diagram occupied by composite active nucleus – HII galaxies; they do not follow the local excitation sequence from SDSS
BPT diagram at $z<1$

- solid line: maximum theoretical starburst line of Kewley et al. (2001): star-forming galaxies fall below and to the left of this line
- dashed line: a similar, empirical determination by Kauffmann et al. (2003)
Some galaxies fall between the two lines: why? (to be analysed with the zCOSMOS data)

They could be composite AGN, or could have different ionization parameters ([OIII]/[OII]) due to changes in the stellar populations (ionizing spectrum) and gas content of the galaxies.
Next steps

• calculate metallicities with 5 emission lines at z~2.3, and enlarge sample at z<1 (reduction of data ongoing)

• compare SFR for all ~40 galaxies from extinction corrected Hα, SFR from [OII] and from mid-infrared COSMOS observations (Paschen-α)

• better statistics to study group/field dependence of [O/H], SFRs etc. with more reduced data

• data are fresh: January-June 2010

• benchmark for galaxies where Hα on night sky lines

• use MOIRCS, LUCIFER, KMOS to enlarge these samples with the wealth of information of the COSMOS survey
Maier et al. 2005: Pegase models with $\text{SFR} \sim \exp(-t/t_1)/t_1$, assuming the galaxy is built up by continuous infall of primordial gas with an infall rate $\sim \exp(-t/t_{\text{inf}})/t_{\text{inf}}$; Models with $t_{\text{inf}} \ll t_1$: closed-box like
Equation of cosmic chemical evolution

- Fall and Pei (1993): equations of cosmic chemical evolution

1. Equation: Conservation of mass: \( \frac{d}{dt}(g+s) = \frac{d}{dt}(f) \), where \( g/s \) is the density parameter in gas/stars, and \( \frac{d}{dt}(f) \) the rate of infall/expulsion of baryonic material from galaxies.

2. Equation: The rate at which the mass of heavy elements changes with time: \( \frac{d}{dt}(m) = \frac{d}{dt}(Z \cdot g) = y \cdot \frac{d}{dt}(s) - Z \cdot \frac{d}{dt}(s) + Zf \cdot \frac{d}{dt}(f) \), where \( m \) is the density parameter in heavy elements, \( y \) the yield, \( Z \) the metallicity.

- Closed Box Model: no infall/expulsion of matter from/into IGM, \( Z = -y \cdot \ln(g(z)/g(\text{initial})) \)
- Infall Model: infalling matter consists of unenriched primordial material gas.
Oxygen abundances: Direct calibration

• Abundance of any ion (e.g. O$^+$) relative to H$^+$: $X(O^+)/X(Hb) = I(3727)/I(Hb)*e(Hb)/e(3727)$; Hydrogen assumed to be completely ionized → abundance relative to hydrogen from summing over all ionization states

• Relative rates of excitation of the $^1S$ and $^1D$ levels depend very strongly on the electron temperature $T_e$

• From the ratio of $[\text{OIII}]b+/[\text{OIII}]a/[\text{OIII}]4363 \rightarrow T_e[O^{++}]$, $T_e[O^+] \rightarrow e(l) \rightarrow O/H$

• Temperature sensitive line $[\text{OIII}]\lambda4363$ line too weak to be detected at medium $z$ → no direct calibration possible

• Energy level diagram for O$^{2+}$
SFRs derivation for zCOSMOS galaxies at 0.5<z<0.9

• for this study I used the [OII]-SFR calibration by Moustakas et al. (2006), which takes dust extinction and metallicity into account, using a correction dependent on the galaxy’s restframe B-band magnitude

• one of the best-understood SFR indicators is Hα: the Hα extinction corrected luminosity is directly proportional to the hydrogen-ionizing radiation from massive stars

• drawback: Hα is redshifted out of the optical window beyond z~0.5 → need near-infrared follow-up
Gas metallicities at $z>0.5$ using near-IR spectroscopy

- Maier, Lilly et al. 2005, ApJ, 634, 849: ISAAC near-IR spectroscopy of $0.5<z<1$ CFRS galaxies

- Measurements of H$\alpha$ and [NII] line fluxes for CFRS galaxies with [OIII], H$\beta$, and [OIII] from optical spectroscopy (Lilly et al. 2003)

- About one third of the CFRS galaxies have lower metallicities than local galaxies with similar luminosities (masses); can still be however on the upper branch or turn-around region of $R_{23}$ relation

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Fig. 1.—ISAAC spectra using the SZ filter for the fifth grating order in order to get H$\alpha$ and [N II] $\lambda$6584 for galaxies at $0.5<z<0.65$. The spectra are smoothed with a Gaussian filter, as described in the text. In each panel, the filled square and the filled triangle show the positions of H$\alpha$ and [N II] $\lambda$6584, respectively. Almost all galaxies show a [N II] $\lambda$6584/H$\alpha$ ratio greater than 0.1, as expected for galaxies that lie on the high-metallicity branch of the $R_{23}$ calibration.
CFRS galaxies with reliable [O/Hs] (Maier et al. 2005): morphology and environment information was missing → available for zCOSMOS galaxies
## Concordance cosmology

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