NIR Spectroscopy of Star-Forming Galaxies at z~1.4 with Subaru/FMOS

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Introduction:

- Gas-phase Metallicity (hereafter, metallicity)
  - Metallicity traces the past star formation activity
  - It also changes via gas infall/outflow of the galaxies
  - This will be a key to understand the galaxy evolution
- It is known that galaxy mass (or luminosity) is correlated with metallicity
  - Massive (bright) galaxies tend to show larger metallicities
  - Stellar mass-metallicity (hereafter, MZ) relation at z\sim0 is established (Tremonti+04)

\[\text{\#53000 SDSS galaxies}\]
Introduction: Mass-Metallicity Relation at $z>1$

- MZ relation at $z\sim 2$ (e.g., Erb+06) and $z\sim 3$ (e.g., Maiolino+08)
  - Evolution of the MZ relation from $z\sim 3$ to $z\sim 0$?
  - Still controversy as to the MZR at $z\sim 2$ (Hayashi+09, Yoshikawa+10, Onodera+10)
  - We need larger sample at $z=1-2$, when the universe in the most active/violent phase

![Diagram of mass-metallicity relation at $z\sim 2$](image)
Introduction: Intrinsic Scatter of Mass-Metallicity Relation

- The MZ relation at z~0.1 has intrinsic scatters (Tremonti+04)
- What physical parameters can explain this scatter?
  - SFR (Mannucci+2010), specific SFR (Ellison+2008), half light radius (Ellison+2008), galaxy interaction (Rupke+2008)
- The intrinsic scatter of the MZ relation at high-z is still unknown
- We need large sample at high-z

![Intrinsic scatter diagram](image1)

![Higher SFR vs. lower SFR](image2)
What’s FMOS (Fibre Multi-Object Spectrograph)?
- Second generation instrument for Subaru Telescope
- Collaboration among Japan, UK, and Australia
- Multi-object spectrograph in NIR (0.9-1.8µm) w/ 400 fibers and FoV of 30’Φ
- Low Resolution (LR; R~650) and High Resolution (HR; R~3000) mode
- Details are in Kimura et al. 2010, PASJ, 62, 1135
- We conduct large NIR spectroscopic surveys with FMOS

Fiber positioner on prime focus

Optical design of FMOS
Sample Selection and Observations:

- **Targeted Sample**
  - Field: SXDS/UDS (effective area\(\sim 0.7 \text{ deg}^2\))
  - \(1.2 < z_{\text{phot}} < 1.6, K < 23.9 \text{ AB mag}, M_* > 10^{9.5} M_{\odot}, F(\text{H}\alpha) > 1.0 \times 10^{-16} \text{ cgs}\)
  - Excluding X-ray sources (\(L_x > 10^{43} \text{ erg/s}\))
  - 2500 objects in whole area of the SXDS

- **Observations**
  - Mainly FMOS/GTOs in 2010-2011
  - LR mode / Cross Beam Switch mode
  - Typical exposure time is 3-4 hrs per FoV
  - About 1200 objects are observed in total

- **Data Reduction**
  - FMOS reduction pipeline FIBRE-pac
  - Details are shown in Iwamuro+12

- **Spectral Fittings**
  - Fitting methods taking the OH mask effects into consideration.
Observed Spectra:

We observed ~1200 targets in total. Among them, 343 objects show significant Hα emission (S/N>3) at $z=1.2-1.6$ (median=1.41). This is the largest NIR spectroscopic sample at $z>1$ ever.

Initial results (GTO in 2010; 71 Hα detections) are already presented by Yabe+12 (arXiv:1112.3704). In this talk, we also present preliminary results of all GTO runs.
AGN Contributions:

- AGN diagnostics from the BPT diagram ([NII]/Hα vs. [OIII]/Hβ)
- Most objects are placed in the SF region in the BPT diagram
- 21 objects are AGN candidates (BPT, extremely large [NII]/Hα ratio and line width)
- Stacking analysis shows that our sample is on the SF region on average
Mass-Metallicity Relation at z~1.4:

- $12+\log(O/H)$ from [NII]/H$\alpha$ line ratio (N2 method; Pettini & Pagel 2004)
- No significant [NII] emission (S/N<3.0) from ~70% of the objects
- Stacking analysis dividing our sample into 3 stellar mass bins (5x10$^9$-1x10$^{11}$ M$_{\odot}$)
- The largest sample ever at z>1

Typical number in each mass bin is ~90
Cosmic Evolution of Mass-Metallicity Relation:

- Comparison to the previous works up to $z \approx 3$
  - ✓ Our results at $z \approx 1.4$ are between those at $z \approx 0.8$ and $z \approx 2.2$
  - ✓ Anti-downsizing-like evolution from $z \approx 1.4$ to $z \approx 0.8$?
- Evolution of the MZ relation from $z \approx 3$ to $z \approx 0$
  - ✓ Smoothly evolves from $z \approx 3$ to $z \approx 0$
  - ✓ MZ relation evolution at $M^* = 10^{10} M_{\odot}$: $12 + \log(O/H) = 8.69 - 0.086(1+z)^{1.3}$

Metallicity calibration and IMF of other works are all the same as ours.
Comparison with the theoretical models:

- Comparison with theoretical predictions (Davé et al. 2011)
  - ✓ N-body + SPH cosmological simulations
  - ✓ 4 wind models (no wind; constant wind; slow wind; mass dependent wind) implemented
    - ✗ Constant wind (cw) : $dM_{\text{wind}}/dt=2xSFR$, $v_{\text{wind}}=680$ km/s
    - ✗ Mass dependent wind (vzw) : velocity dispersion (=mass) dependent wind
- Our result agrees with cw or vzw model

comparison with Davé+11 model

Metallicity calibration and IMF of other works are all the same as ours
We found that the MZ relation at $z \sim 1.4$ has intrinsic scatters of $\sim 0.1$ dex.

✓ Observational errors are subtracted from the observed scatters
✓ Well agrees with SDSS results at $z \sim 0.1$ within the error bars
✓ However, note that the values should be lower limit because some metallicities are upper limit

What makes the intrinsic scatter?

**Intrinsic Scatter of Mass-Metallicity Relation:**

[$\text{[NII]}$ S/N$>3$

$\circ$ [$\text{[NII]}$ 3$>$S/N$>1.5$

$\downarrow$ [$\text{[NII]}$ S/N$<1.5$

Typical Observational Error

**Scatter ($\sigma$)**
Second Parameter Dependency (Yabe+12):

- Dependency of SFR and size on the MZ relation
  - SFR : derived from Hα luminosity corrected for the dust extinction
  - We take half light radius ($R_{50}$) as galaxy size (from K-band image)
  - Dividing the sample into three groups by the parameter
  - Stacking analysis in each group
- Galaxies with larger SFRs and size tend to show lower metallicities

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**Initial results (Yabe+12)**

- Stellar Mass ($M_\odot$)
  - High SFR (Stack)
  - Low SFR (Stack)
  - Middle SFR

- Solar abundance

- SFR : derived from Hα luminosity corrected for the dust extinction
- We take half light radius ($R_{50}$) as galaxy size (from K-band image)
- Dividing the sample into three groups by the parameter
- Stacking analysis in each group
- Galaxies with larger SFRs and size tend to show lower metallicities
Second Parameter Dependency (this work):

- Dependency of SFR and size on the MZ relation
  ✓ Methods are all the same as before
  ✓ The dependency of SFR on the MZ relation disappears in the least massive bin
  ✓ The dependency of $R_{50}$ still survives
Morphological trends (very preliminary):

- About 50 objects in the CANDELS/UDS field are observed with FMOS
- For these objects, morphological properties can be examined as well as metallicities

- Diffuse and disk dominated galaxies tend to show lower metallicity than compact and bulge dominated galaxies?
- This result and the size dependency may support the “Different Evolutionary Stage” scenario:
  ✓ Galaxies with smaller size have higher gas surface density
  ✓ These are rapidly grown in the past and chemically evolved
  ✓ These are also morphologically evolved?

The trend is still vague, so we need larger sample in the CANDELS fields.
Summary:

- We observed star-forming galaxies at $z \sim 1.4$ are measured with Subaru/FMOS.
- We detected H$\alpha$ line from $\sim 300$ objects with significance of $S/N > 3$.
- Gas-phase metallicity is derived from $[\text{NII}]/\text{H}\alpha$ line ratio.
- We construct the mass-metallicity (MZ) relation at $z \sim 1.4$ with the largest sample ever.
- By comparing previous results:
  - ✓ The MZ relation evolves smoothly from $z \sim 3$ to $z \sim 0$.
  - ✓ They agree with theoretical models with wind.
- The MZ relation at $z \sim 1.4$ has an intrinsic scatter of $\sim 0.1$ dex.
- We examined the dependency of physical parameters on the MZ relation for the scatter:
  - ✓ Clear trend for size: Galaxies with larger $R_{50}$ tend to show lower metallicity.
  - ✓ No clear trend for SFR: Disagree with that at $z \sim 0.1$ by Mannucci+10.
- Preliminary results show the morphological dependence:
  - ✓ Bulge-dominated galaxies are located in the upper region on the MZ relation.
  - ✓ Disk-dominated galaxies are located in the lower region on the MZ relation.
  - ✓ “Different evolutionary stage” scenario may be plausible.
  - ✓ Further observations in the CANDELS field are required.