The ALPINE-ALMA [C II] survey: Investigation of 10 galaxies at $z \sim 4.5$ with [O II] and [C II] line emission – ISM properties and [O II]–SFR relation

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[1. Introduction]

1-1. Previous papers:

- Robert C. Kennicutt (1998):
  - relation between [O II] and SFR to local starburst galaxies
- Lisa J. Kewley, Geller & Jansen (2004):
  - Like Hα, [O II] is also associated with SFR
  - However, since [O II] is a forbidden line, [O II] is sensitive to the gas-phase metallicity, ionization state (= have a degeneracy)
  - [O II]: not directly coupled to the ionizing radiation from young stars
  - [O II]-SFR relation is expected to vary significantly with physical properties and redshift

1-2. Goals of this research:

- To test whether the locally calibrated SFR([O II]) relation remains valid at z ~ 4.5.
- Indirect estimation of metallicity using UV absorption lines.
- constrain ISM physical properties (metallicity, electron density, and the ionization parameter) using Hα and [C II]

[2. Sample and Data]

2-1. Targets:

- COSMOS field
- 10 main-sequence ALPINE galaxies at z ~4.5
  - ALPINE survey: observed [C II] 158 μm emission line at z ~ 4.5–5.9 with ALMA.
- log (M / M) = 9.2 –11.1 (not include low-mass galaxy)
- SFR = 23 –190 M/yr

2-2. Multi-wavelength data acquisition:

- Optical [O II] emission line:
  - 1 galaxy from Keck/MOSFIRE spectroscopy
  - 9 galaxies from Subaru/MOIRCS narrow-band imaging
- Hα emission line: from Spitzer photometry
- Rest-UV absorption lines: from Keck/DEIMOS spectroscopy
- [C II] 158 μm emission line & 150 μm dust continuum: from ALMA

➔ allow to analyze the relation between **[O II]-SFR** and the interstellar medium (ISM) properties via **[O II]/[C II]** and **[O II]/Hα** luminosity ratios.

2-3. Calculate SFR and physical parameters

- SFR_{total} = SFR_{UV} + SFR_{IR}
  - SFR_{UV} : unobscured SF
  - SFR_{IR} : dust obscured SF
- Physical properties (stellar mass, SFR, E(B−V), UV slope (β)): estimated using rest-frame UV–optical photometry & SED fitting
- Stellar population model: Gustavo Bruzual & Stéphane Charlot (2003)

The SFR_{total} in Figure 1 is calculated from the data in Table 2 using one of the following methods:

- Method 1) If both UV and far-infrared continuum data are available:
  - use Robert C. Kennicutt (1998) and Kennicutt & De Los Reyes (2021) equations

$$\mathrm{SFR_{UV}}\ \left(\mathrm{M_\odot\ yr^{-1}}\right) = 0.79 \times 10^{-28} L_\nu$$

$$\mathrm{SFR_{IR}}\ \left(\mathrm{M_\odot\ yr^{-1}}\right) = 2.54 \times 10^{-44} L_{\mathrm{IR}}$$

- Method 2) If either UV or far-infrared continuum data are unavailable:
  - [C II]–SFR relation (Schaerer et al. 2020) is used.

$$\log\left(\mathrm{SFR_{[CII]}}/\left[\mathrm{M_\odot\ yr^{-1}}\right]\right) = \frac{\log(\mathrm{L_{[CII]}}/\mathrm{L_\odot}) - 6.61}{1.17}$$

  - (Reference) [C II]–SFR relation from De Looze et al. (2014) & Schaerer et al. (2020):
    - metal-poor dwarf : SFR underestimate (~0.43 dex)
    - ULIRG : SFR overestimate (~0.77 dex)

Table 2. Summary of properties derived from the ancillary data for the nine galaxies with [O II] detection from narrow-band imaging.

ID	$z_{[CII]}$	$\log(L_{OII})$ ($L_\odot$)	$\log(L_{[CII]})$ ($L_\odot$)	$\log(L_{FIR})$ ($L_\odot$)	$\log(M)$ ($M_\odot$)	$SFR_{[CII]}$ ($M_\odot\ yr^{-1}$)	SFR_{FIR} ($M_\odot\ yr^{-1}$)	SFR_{UV} ($M_\odot\ yr^{-1}$)
DC_665626	4.5830	$9.36^{+0.08}_{-0.09}$	$8.21^{+0.10}_{-0.13}$	–	$9.21^{+0.16}_{-0.18}$	$23.15^{+1.22}_{-1.30}$	–	$5.77^{+1.24}_{-1.23}$
DC_680104	4.5320	$9.51^{+0.10}_{-0.13}$	$8.74^{+0.12}_{-0.16}$	–	$9.23^{+0.18}_{-0.12}$	$66.30^{+1.25}_{-1.36}$	–	$14.55^{+1.12}_{-1.10}$
VC_5100969402	4.5869	$9.34^{+0.08}_{-0.10}$	$8.72^{+0.04}_{-0.05}$	$11.65^{+0.11}_{-0.16}$	$10.00^{+0.14}_{-0.12}$	$63.42^{+1.09}_{-1.10}$	$43.23^{+13.06}_{-13.06}$	$12.50^{+1.14}_{-1.13}$
VC_5100994794	4.5783	$9.14^{+0.11}_{-0.15}$	$8.75^{+0.04}_{-0.04}$	$11.20^{+0.12}_{-0.16}$	$9.73^{+0.13}_{-0.15}$	$66.93^{+1.08}_{-1.09}$	$15.50^{+4.71}_{-4.71}$	$10.69^{+1.19}_{-1.23}$
VC_5101209780	4.5700	$8.99^{+0.30}_{-0.38}$	$8.86^{+0.08}_{-0.10}$	$11.62^{+0.13}_{-0.19}$	$10.05^{+0.12}_{-0.12}$	$84.45^{+1.18}_{-1.23}$	$40.65^{+14.64}_{-14.64}$	$22.07^{+1.09}_{-1.10}$
VC_5101210235	4.5733	$9.06^{+0.16}_{-0.30}$	$8.35^{+0.11}_{-0.14}$	–	$9.78^{+0.15}_{-0.12}$	$30.71^{+1.24}_{-1.33}$	–	$24.08^{+1.08}_{-1.07}$
VC_5101218326	4.5678	$9.32^{+0.08}_{-0.10}$	$9.26^{+0.02}_{-0.02}$	$11.79^{+0.07}_{-0.08}$	$11.01^{+0.05}_{-0.07}$	$184.45^{+1.04}_{-1.04}$	$60.38^{+10.30}_{-10.30}$	$27.94^{+1.06}_{-1.07}$
VC_5101244930	4.5769	$9.09^{+0.30}_{-0.19}$	$8.70^{+0.08}_{-0.10}$	–	$9.67^{+0.13}_{-0.16}$	$61.73^{+1.18}_{-1.23}$	–	$17.45^{+1.12}_{-1.12}$
VC_5110377875	4.5441	$9.21^{+0.18}_{-0.32}$	$9.23^{+0.03}_{-0.03}$	–	$10.17^{+0.21}_{-0.12}$	$174.87^{+1.05}_{-1.06}$	–	$24.67^{+1.09}_{-1.08}$

Note. The UV SFRs have not been corrected for dust attenuation. [C II] SFRs derived using the Schaerer et al. (2020) relation (see Section 3.1.1). Far-infrared SFRs derived using the Kennicutt (1998) relation.

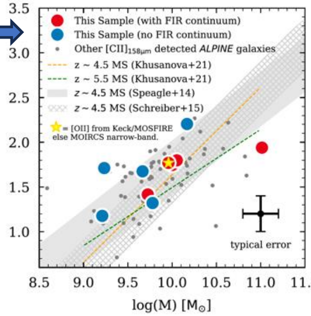

Figure 1. SFR_{total} vs. stellar mass

➔ The SFRs derived using these two methods are in good agreement with the z ~ 4.5 main sequence from Marcel Speagle et al. (2014) and Cyril Schreiber et al. (2015)

2-4. Calculate metallicity: use UV absorption

Upper panel:

- The stacked rest-frame UV spectrum of 10 galaxies (due to the low S/N)
- Shaded region: 1σ scatter

Lower panel:

- Estimate metallicity: using EWs of rest-frame UV absorption lines
- Gray region: EW–metallicity calibration (Peter L. Faisst et al. 2016)
- Blue region: EWs measured from the stack of the 10 galaxies
- Vertical dashed lines: 0.1, 0.5, 1.0 $Z_\odot$

Metallicity of stacked galaxies:

$$12 + \log(O/H) = 8.41^{+0.31}_{-0.54}$$

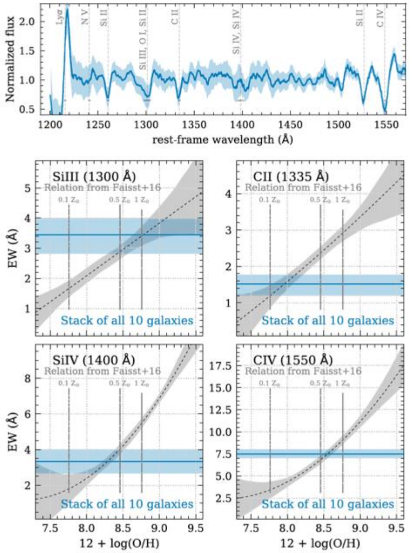

Figure 4. Estimate metallicity using UV absorption lines

2-5. Measure [O II] flux (from narrow-band imaging)

Narrow band flux density = emission line + continuum

$$\bar{f}_\lambda^{NB} = \frac{\int f_\lambda T_\lambda^{NB} d\lambda}{\int T_\lambda^{NB} d\lambda} = \frac{\int (f_\lambda^{line} + f_\lambda^{cont}) T_\lambda^{NB} d\lambda}{\int T_\lambda^{NB} d\lambda}$$

Broad band flux density ~ almost continuum

$$\bar{f}_\lambda^{Ks} = \frac{\int f_\lambda T_\lambda^{Ks} d\lambda}{\int T_\lambda^{Ks} d\lambda} \approx f_\lambda^{cont}$$

Calculate [O II] flux: $F_{line} = (\bar{f}^{NB} - \bar{f}^{Ks}) \times \Delta\lambda_{NB}$

[3]. Discussion

3.1 Dust estimation

- If FIR data is available → $\log(\frac{L_{IR}}{L_{UV}})$
  - Meaning: The ratio of UV light absorbed by dust
- If FIR data are not available → β slope or SED fitting

3.2 [O II]-SFR relation at z~4.5

- Kennicutt (1998): SFR overestimated by 3–5 times

$$\mathrm{SFR^{K98}_{[O\,II]}}\ (\mathrm{M_\odot\ yr^{-1}}) = (0.79 \pm 0.23) \times 10^{-41} L_{[\mathrm{OII}]}\ (\mathrm{erg\,s^{-1}})$$

- Kewley et al. (2004): close to the data

$$\mathrm{SFR^{K04}_{[O\,II]}}\ (\mathrm{M_\odot\ yr^{-1}}) = (3.72 \pm 0.93) \times 10^{-42} L_{[\mathrm{OII}]}\ (\mathrm{erg\,s^{-1}})$$

- Kewley et al. (2004) – metallicity dependent relation: most similar

$$\mathrm{SFR^{K04}_{[O\,II]}}(Z)\ (\mathrm{M_\odot\ yr^{-1}}) = \frac{4.46 \times 10^{-42} L_{[\mathrm{OII}]}\ (\mathrm{erg\,s^{-1}})}{(-1.75 \pm 0.25)[\log(\mathrm{O/H}) + 12] + (16.73 \pm 2.23)}$$

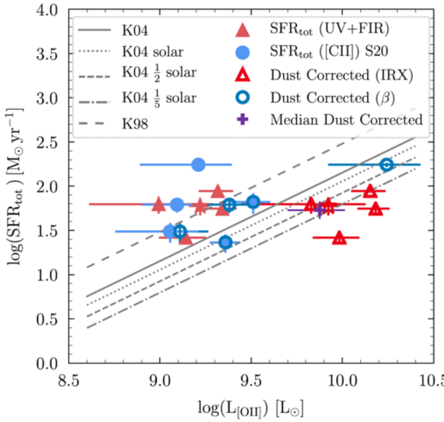

Figure 5. Relation between [O II] and SFR_{total}

3.3 Constraining ISM Physical Properties (using CLOUDY)

Physical meaning of line ratio

- L_[OII]/L_Ha: How strong [O II] is at a fixed SFR
- L_[OII]/L_[CII]: Relative contribution of ionized gas vs. neutral gas
- [O II]: have a degeneracy with metallicity, ionization parameter(U), electron density (n) -> reflect in [Figure 6]

Stellar population assumptions

- (A) Instantaneous burst
- (B) Constant star formation
- (C) Best-fit SED for DC 881725

Left Column: log(L[O II]/L_Hα)

- Horizontal line: median value of individual galaxies (because Hα is derived from photometric data, so it has large uncertainties)
- Gray shaded region : 1σ uncertainty

Right Column: log(L[O II]/L[C II])

- Thick horizontal line: DC 881725 (with the 1σ uncertainty)
- Thin horizontal line: Nine narrow-band selected galaxies

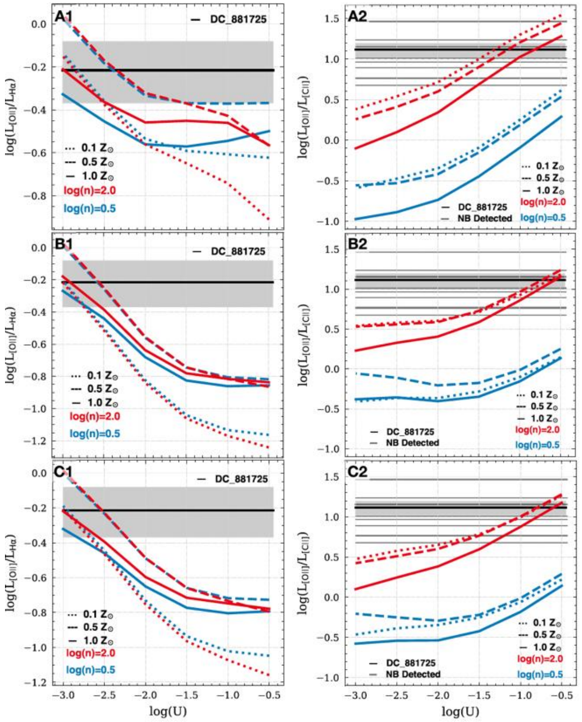

Figure 6. Constrain ISM properties using CLOUDY

Result of [Figure 6]

(1). log(L[OII]/LHα)

- U ↑ → ratio ↓
- Weak dependence on electron density
- Weak dependence on metallicity
- $\log(U) < -2$

(2). log(L[OII]/L[CII])

- U ↑ → ratio ↑
- density ↑ → ratio ↑
- metallicity ↑ → ratio ↓
- electron density (assuming metallicity ≈ 0.5 $Z_\odot$): $log(n/cm^3)$ ~ 2.5 – 3

4. Conclusion

- First calibration of the [O II]–SFR relation at z ~ 4.5, using total SFRs derived from [C II] and FIR data.
- [O II]-SFR_{total} relation is best explained by the subsolar metallicity model of Lisa J. Kewley et al. (2004).
- ISM physical conditions derived from CLOUDY (note that these results depend on the model assumptions):
    - log(U) < −2
    - Electron density: $\log(n/cm^3) \approx 2.5$–3