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CEERS Key Paper. VIII. Emission-line Ratios from NIRSpec and NIRCam Wide-Field Slitless Spectroscopy at $z > 2$

Abstract

We use James Webb Space Telescope Near-Infrared Camera Wide Field Slitless Spectroscopy (NIRCam WFSS) and the Near-Infrared spectrograph (NIRSpec) in the Cosmic Evolution Early Release survey to measure rest-frame optical emission-line ratios of 155 galaxies at $z > 2$. The blind NIRCam grism observations include a sample of galaxies with bright emission lines that were not observed on the NIRSpec masks. We study the changes of the Hα, [O III]/Hβ, and [Ne III]/[O II] emission lines in terms of redshift by comparing to lower-redshift SDSS, CLEAR, and MOSDEF samples. We find a significant (>3σ) correlation between [O III]/Hβ with redshift, while [Ne III]/[O II] has a marginal (2σ) correlation with redshift. We compare [O III]/Hβ and [Ne III]/[O II] to stellar mass and Hβ SFR. We find that both emission-line ratios have a correlation with Hβ SFR and an anticorrelation with stellar mass across the redshifts $0 < z < 9$. Comparison with MAPPINGS V models indicates that these trends are consistent with lower metallicity and higher ionization in low-mass and high-SFR galaxies. We additionally compare to IllustrisTNG predictions and find that they effectively describe the highest [O III]/Hβ ratios observed in our sample, without the need to invoke MAPPINGS models with significant shock ionization components.

- Data: rest-frame optical emission-line ratios of 155 galaxies at $z > 2$.
- Goal: study the changes of the Hα, [O III]/Hβ, and [Ne III]/[O II] emission lines in terms of redshift
- Results:
  1. significant (>3σ) correlation between [O III]/Hβ with redshift
  2. marginal (2σ) correlation between [Ne III]/[O II] with redshift
  3. both emission-line ratios ([O III]/Hβ and [Ne III]/[O II]) have a correlation with Hβ SFR and an anticorrelation with stellar mass across the redshifts $0 < z < 9$
  4. these trends are consistent with lower metallicity and higher ionization in low-mass and high-SFR galaxies

[1]. Introduction

- Why emission line is important?
  - determine a galaxy's interstellar medium (ISM) conditions, physical properties. and dust attenuation

- How to analyze the emission line?
  - by comparing ratios of lines at similar wavelengths
  - picking emission-line ratios with similar wavelength makes the ratio less sensitive to dust attenuation

- Why did they study the [O III]/Hβ and [Ne III]/[O II] emission lines?
  - Due to the higher ionization, lower metallicity, and α-element enhancement of star-forming galaxies at z ~ 2
    -> the BPT and VO87 (Veilleux & Osterbrock 1987) diagrams are not effective at distinguishing star-forming galaxies from AGN

[2]. Observational data and sample

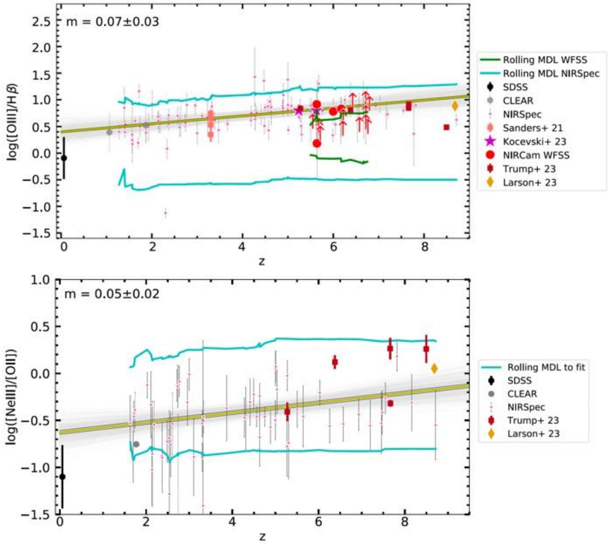
2.1 JWST WFSS and MSA Spectroscopy
- galaxy sample comes from JWST observations taken by the CEERS program
- 18 galaxies with Hα in the redshift range 4 < z < 5 from the NIRCam WFSS.
- 19 galaxies with [O III] in the redshift range 5.5 < z < 7 from the NIRCam WFSS.

2.2 Stellar Mass
- Stellar masses and dust attenuations come from fitting the optical and NIR SEDs using FAST (Kriek et al. 2009).

2.3 Other Comparison Samples
- z ~ 0 comparison sample: SDSS
- z ~ 2 comparison sample: CANDELS Lyα Emission at Reionization (CLEAR) survey + 3D-HST program
- z ~ 3 comparison sample: MOSDEF

[3]. Redshift Evolution of Emission-line Galaxies

- The increase of [O III]/Hβ with redshift is shown in the linear fit line, with a slope of (0.07 ± 0.03).
- The NIRSpec [Ne III]/[O II] line ratio has a 2.5σ slope with redshift, (0.05 ± 0.02), as shown by the yellow best-fit line.



[Figure 5].
Top: The log[O III]/Hβ emission-line ratio vs. redshift.
Bottom: The log[Ne III][O II] emission-line ratio vs. redshift.
The NIRSpec and WFSS samples are represented by pink points and red points. The yellow line is the linear best fit to the NIRSpec. The cyan lines represent the rolling median detection limit (MDL) to the best-fit line for the NIRSpec galaxies.

[4]. Emission-line Properties with Galaxy Stellar Mass and SFR

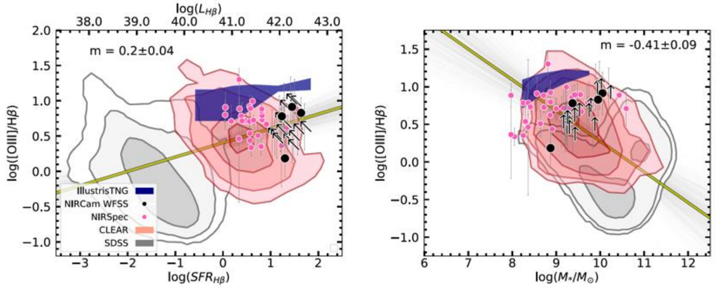
- Figure 8 compares [O III]/Hβ ratio to Hβ SFR and stellar mass.
- Figure 9 compares [Ne III]/[O II] ratio to Hβ SFR and stellar mass.
  - SFR is calculated from either the Hβ or Hα emission line by following the Kennicutt & Evans (2012) SFR relation

$$\log(\mathrm{SFR})[M_\odot\ \mathrm{yr}^{-1}] = \log[L(\mathrm{H}\beta)] - 40.82 \quad (1)$$

$$\log(\mathrm{SFR})[M_\odot\ \mathrm{yr}^{-1}] = \log[L(\mathrm{H}\alpha)] - 41.27. \quad (2)$$

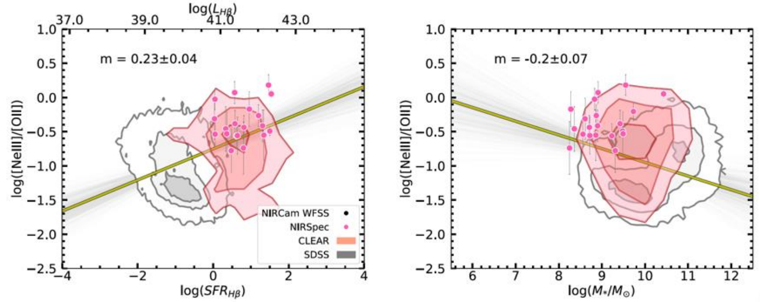
- The [O III]/Hβ emission-line ratio has
  - a significant (>3σ) correlation with Hβ SFR, with a slope of 0.2 ± 0.04,
  - a significant anticorrelation with stellar mass, with a slope of −0.41 ± 0.09.

Here, the NIRCam WFSS and NIRSpec samples are at z > 5



[Figure 8]. Left: The relationships between the [O III]/Hβ emission-line ratio and the galaxy Hβ luminosity and Hβ SFR. Right: The relationships between the [O III]/Hβ emission-line ratio and stellar mass.

- The [Ne III]/[O II] ratio has
  - a significant correlation with Hβ SFR, with a slope of 0.23 ± 0.04,
  - a marginal (2σ) anticorrelation to stellar mass with a slope of −0.2 ± 0.07

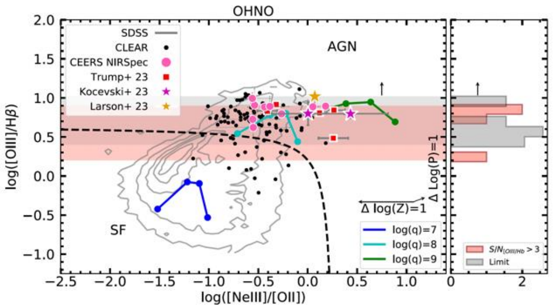


[Figure 9]. Left: The relationships between the [Ne III]/[O II] emission-line ratio and the galaxy Hβ luminosity and Hβ SFR. Right: The relationships between the [Ne III]/[O II] emission-line ratio and stellar mass.

-> The anticorrelation between log([O III]/Hβ) and stellar mass is due to lower metallicity and higher ionization in galaxies with higher specific star formation rates (sSFR). (Dickey et al. 2016 and Kashino et al. 2019)

[5]. ISM Conditions at z>5

- They compare measurements of [O III]/Hβ and [Ne III]/ [O II] to theoretical models to infer the physical conditions of the ISM



[Figure 11]. Theoretical OHNO line ratio predictions from the MAPPINGS V models (colored lines) compared to galaxies with different redshift epoch

- The galaxies that are in the AGN region of the diagram have higher ionization.
- Their z > 5 sample prefers a moderate to high ionization, log(q) = 8, 9

[6]. Summary

- Studied optical emission-line ratios from z ~ 0 to z ~ 9 using SDSS, CLEAR, and CEERS data sets

1) CEERS samples show a 3σ correlation between [O III]/Hβ with redshift, 0.07 ± 0.03
2) 2σ correlation with [Ne III]/[O II] with redshift, 0.05 ± 0.02.
3) Hα SFR has a slope of 0.18 ± 0.03 with redshift
4) [O III]/Hβ and [Ne III]/[O II] both have correlations with Hβ SFR, with slopes of 0.2 ± 0.04 and 0.23 ± 0.04
5) [O III]/Hβ and [Ne III]/[O II] both have anticorrelations with stellar mass with a slope of −0.41 ± 0.09 and −0.2 ± 0.07.
6) Comparing the CEERS line ratios with z ~ 0 and z ~ 2 samples indicates that the ISM ionization increases with increasing redshift.