CECILIA: Ultra-Deep Rest-Optical Spectra of Faint Galaxies at Cosmic Noon

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1. What is CECILIA?

- Chemical Evolution Constrained Using Ionized Lines in Interstellar Aurorae
- A program that uses JWST's NIRSpec/Multi-Slit Spectroscopy to detect auroral lines inside galaxies and track changes in electron temperature and composition.

2. Observation Target

- Low metallicity and low-mass galaxies at z=2-3.
- Target: nine low-luminosity galaxies ($M_{UV} \approx -17\sim-20$) & low-mass ($M \lesssim 10^9\ M_\odot$)
  - Four sources (NB2929, NB2089, NB2875, NB2571): Lyα emitters (LAEs) from KBSS-Lyα survey
    - KBSS: A large-scale spectroscopic survey to comprehensively study galaxies and the surrounding intergalactic matter in the high redshift (z ~ 2~2.5) universe.
  - Three sources (fBM40, fBM47, and fC23): from the KBSS on the basis of their rest-UV continuum colors using the three-band (UnGR) criteria
  - Two sources (C31b and BX587b): visually identified in the 2D spectrograms of the primary sources

3. Observation

- Through observations of JWST/NIRSpec G235M (1.7–3.1 μm)/ F170LP (170–200 nm) (≈29.5 hours) and G395M (2.9–5.0 μm)/ F290LP (290–400 nm) (1 hour)

4. Importance of this research

- Low-mass and low-metallicity galaxies are analogs to reionization-era galaxies, contributing to reionization research.
- Very long exposure times allowed us to obtain spectral data on extremely faint galaxies previously unobservable.

Table 1. Galaxy Names and Properties

Galaxy Name	Redshift	Lyα EW (Å)	M_{UV}	E(B-V)	SFR ($M_\odot$/year)
Q2343-NB2929	2.546	23^{+19}_{-10}	−18.99	0.43 ± 0.21	$1.26^{+0.88}_{-0.35}$
Q2343-NB2089	2.571	73^{+130}_{-46}	> −17.29	0.28 ± 0.11	$1.54^{+0.51}_{-0.30}$
Q2343-NB2875	2.545	320^{+580}_{-78}	> −17.74	0.05 ± 0.07	$0.86^{+0.15}_{-0.11}$
Q2343-NB2571	2.577	47^{+93}_{-34}	−17.21	0.07 ± 0.08	$0.63^{+0.14}_{-0.10}$
Q2343-fBM47	2.278	20^{+5}_{-5}	−20.65	0.19 ± 0.14	$2.88^{+1.32}_{-0.67}$
Q2343-fBM40	2.147	...	−20.43	0.19 ± 0.12	$3.31^{+1.17}_{-0.67}$
Q2343-fC23	2.173	-9^{+3}_{-3}	−19.85	0.47 ± 0.29	$3.94^{+5.42}_{-1.34}$
Q2343-C31b	3.022	...	...	0.23 ± 0.18	$1.49^{+0.87}_{-0.38}$
Q2343-BX587b	2.775	...	...	0.95 ± 0.23	$5.43^{+4.98}_{-1.61}$

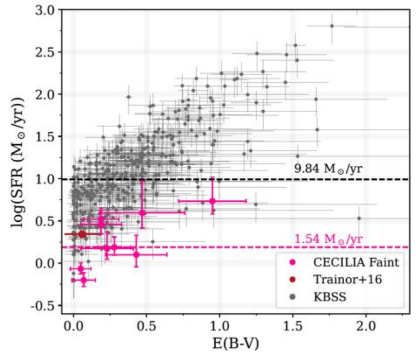
Note—Names and properties of the galaxies included in this investigation. The last two entries of the table refer to the serendipitous sources. $E(B-V)$ and SFRs are calculated using previous Keck/MOSFIRE measurements (S17) for the CECILIA fLBGs.

5. Result

5-1. Star Formation Rate and Dust

- The SFR measured through the Balmer series ranges from 0.63 to 5.43 $M_\odot$/yr (log scale: -0.2 to 0.735), which is systematically lower than that of continuum-selected galaxies from the same epoch.
- The E(B–V) values range widely, from 0 to 1, and it is notable that some galaxies exhibit virtually no dust extinction.

Figure 5. Log(SFR) versus $E(B-V)$ for the CECILIA-faint sample (pink circles), the T16 KBSS-Lyα stack point (brown circle), and KBSS LBGs from S17 (gray circles). The horizontal dashed pink line indicates the median SFR of the CECILIA-faint sample, while the dashed black line marks the median SFR for the KBSS points. A positive correlation is seen between dust attenuation and SFR across the samples.



5-2. Electron Density and Metallicity

- Estimate electron densities using the [S II] λ6717/λ6731 ratio
- $n_e \lesssim 200\ cm^{-3}$, indicating a predominantly low-density ISM environment.
- low [NII]/Hα, and high [OIII]/Hβ, suggesting metallicities of 12 + log(O/H) ≲ 8.0
  - This makes it important as an analogue of reionization-era galaxies.

BPT diagram

- Left: Stacks of target galaxies
- Right: Zoomed-in view of only the CECILIA galaxies.
- Box data: fLBG (faint Lyman Break Galaxy)
- Here, D40 refers to Q2343-D40, a well-studied galaxy in the CECILIA program.

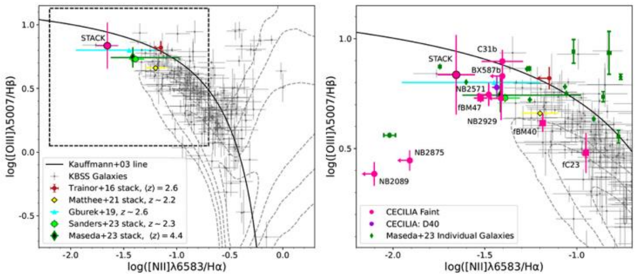


Figure 6. *Left:* N2-BPT diagram (Baldwin et al. 1981) with SDSS $z\sim0$ galaxies (gray, contour lines), KBSS LBGs (S17; gray dots with 3 σ detections for every line), a lensed dwarf galaxy (Gburek et al. 2019), stacks of faint LAEs (T16; Matthee et al. 2021; Maseda et al. 2023), stack of high-z galaxies (Sanders et al. 2023), and the CECILIA stack of the faint galaxies (pink point). The solid black line is the classification curve used by Kauffmann et al. (2003) as a lower limit for finding AGN. The dashed box highlights the region shown in the zoomed-in version. *Right:* Zoomed-in N2-BPT diagram showing individual CECILIA faint galaxies (pink points; 2σ limits, with squares indicating fLBGs), the $z\sim3$ SF galaxy Q2343-D40 observed with JWST/NIRSpec as part of the CECILIA program (purple point), and individual data points from Maseda et al. (2023).

5-3. Extremely low metallicity galaxy

- Two galaxies (NB2975 and NB2089): exhibit high Lyα equivalent widths and low [NII]/Hα, but low [OIII]/Hβ
  - suggesting the presence of [OIII]/Hβ turnover at very low metallicity.
- It highlights the need for diagnostic indicators such as N2 in the identification of metal-poor galaxies.

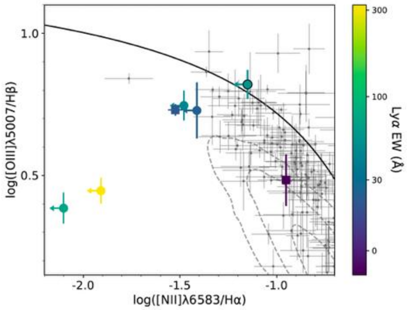


Figure 11. N2-BPT diagram with the same features as Figure 6, but excluding all stacked points and galaxies without reported Lyα EWs. CECILIA faint sources are shown as circles for narrow-band detections and squares for fLGBs. The T16 stack point is plotted as a circle with a black outline. All points are color-coded by their Lyα EWs.

6. Explanation of [OIII]/Hβ turnover

Relation between O3 and metallicity

- O3 ≡ [O III] λ5008 / Hβ -> This ratio can be used to estimate the metallicity of a galaxy.
- **high O3 value** is considered to indicate a galaxy with a high probability of being **low metallicity**.

Relation between N2 and metallicity

- Since nitrogen is produced through secondary nucleosynthesis, the nitrogen content generally increases more rapidly with higher metallicity (Z).
- **Low N2 → Low metallicity**
- N2 is often used as a primary indicator of metallicity (Pettini & Pagel 2004, etc.).

Problem Statement: O3 may be low in extremely low metallicities

- NB2975, NB2089: have large Lyα equivalent widths (EW) and very low [N II]/Hα
  - suggesting extremely-low metallicity.
- However, [O III]/Hβ (O3) values are low.
- In other words, contrary to general expectations, **O3 values are low** even in **extremely low metallicities**.

Why does this phenomenon occur? — O3 turnover

- As metallicity decreases, O3 initially increases. (This is due to the increased ionization and the stronger [O III] emission.)
- However, upon entering the **very low-Z metallicity** region, changes in electron density and cooling efficiency lead to a turnover phenomenon, where **[O III] emission actually weak.**

➔ **O3 value does not increase infinitely** as metallicity decreases.

- This is a phenomenon predicted theoretically.

Conclusion: O3 alone cannot identify ultra-low metal content.

Indicators	Interpretation
Low N2	Low metallicity
Low O3	- Normally: High metallicity - Possible: Extremely low metallicity (turnover is happend)
Both O3 and N2 are low	Extremely low metallicity

- The O3 index alone is not sufficient to properly identify extremely low metallicity galaxies (N2 is also required).

7. Summary

- providing the most sensitive rest-optical spectra of individual faint galaxies
- faint galaxies observed by JWST/NIRSpec:
  - have low metallicity, high ionization, and low SFR,
  - strong Lyα emission is closely linked to decreased metallicity.
- O3 line alone cannot accurately determine a galaxy's metallicity and ionization state
- the current sample is limited to nine galaxies and future sample expansion is needed.