

[O III] line ratios and evolution of oxygen abundance with redshift using JWST-VLT-Keck observations

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ABSTRACT

Understanding chemical evolution of galaxies has been dramatically revised by JWST observations up to high redshifts $z \sim 14$. Complemented by VLT and Keck observations, they reveal metal-rich systems forming within a few hundred million years after the Big Bang. Using new atomic data, we analyze or re-analyze reportedly observed O III line ratios in high-redshift galaxies to derive electron temperatures, densities, and oxygen abundance. In addition to [O III] temperature diagnostics, [O II] and [S II] ratios are employed for density constraints and contour plots of physical conditions. We examine the temperature–abundance relations and track the evolution of [12 + log(O/H)] with redshift. Our [O III] atomic model incorporates recombination-cascade contributions to forbidden lines using new level-specific recombination rate coefficients and transition probabilities, together with collision strengths computed in our earlier works. We find that individual galaxies show a large variation with electron temperature in the nebular range 5000–25000K and O-abundance down to 6.75 compared to the solar value 8.70. The oxygen abundances vs. z display a systematic decrease toward high- $z \sim 10$, with a best fit ranging from 8.25 to 7.50 from the present epoch at $z = 0$. The present analysis employs a collisional-radiative-recombination model that also considers possible (e + O IV) → O III recombination-cascade contributions to [O III] forbidden lines, but which is found to be negligible. That implicitly implies that the analysis refers to nebular H II regions per se, and not to possibly AGN contributions that might involve higher ionization states. We also explore AI Machine Learning models to predict and complement directly derived results, with preliminary simulations trained on observed flux ratios and PyNeb-simulated datasets that are promising but limited by current sample sizes. Future work may expand datasets and refine statistical models to establish robust constraints on early-universe chemical evolution.

Key words: keyword1 – keyword2 – keyword3

1 INTRODUCTION

Space-based observations of distant high- z galaxies by the James Webb Space Telescope (JWST) have definitively established that galaxy formation began much earlier than believed hitherto. That became evident from a number of clearly resolved atomic lines from several elements. Furthermore, since the observed spectra are in the near-IR range the observations can also be verified and complemented by ground-based observations, particularly by high-resolution spectrographs at large telescopes such as Keck and Very Large Telescope (VLT) observatories. Thus optical or even near-UV lines are observable from red-shifted objects. Since JWST spectra became available, it was noticed that several well-known lines of oxygen ions were prominent in the spectra of galaxies out to $z \sim 10$ or greater. As oxygen is one of the most common elements, its abundance would therefore be a reliable indicator of the chemical evolution of the universe if determined accurately and from a sufficient number of galaxies. In our sample we consider the earliest one

at $z \sim 10$ (Abdurro'uf et al. 2024, Hsiao et al. 2025, Hsiao et al. 2024), and the latest at $z \sim 1$ (Welch et al. 2024).

One oxygen ion, O III, well-known in observations from nebular and AGN H II regions, stands out in many of these JWST observations. The forbidden [O III] lines have been studied extensively and are used widely as temperature diagnostics in H II regions in the range 1000–20,000 K. In addition, forbidden [O II] and [S II] lines are employed as electron density diagnostic. Together, these ions provide temperature-density information which, in turn, can be parametrized to derive oxygen abundance since only a few ionization states are involved. Useful expressions dependent on temperature and density have long been utilized obtain abundances in H II regions (e.g. Izotov et al. 2006, Mendez-Delgado et al. 2023).

A recent work has applied strong line calibration on deriving 12 + log(O/H) versus z relation out to $z \sim 3.3$ using data from earlier instruments such as Keck for certain masses of galaxies (Jain et al. 2025). The JWST data with considering the theoretical atomic models is more accurate to consider high redshift galaxies out to $z \sim 10$.

The primary requirement in order to employ theoretical models to analyze observations is accurate atomic data for relevant physical

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processes. In the case of forbidden lines, which usually arise from transitions among low-lying energy levels, those data entail electron impact excitation and radiative transition probabilities. The dominant transitions are among levels of the ground configuration of the same parity via magnetic dipole (M1) and electric quadrupole (E2) transitions. The high-precision atomic data have been computed for all ions under study: O II, O III and S II. We employ these data in a spectral modeling code SPECTRA that constructs a radiative-collisional atomic model with a 5-level energy structure to obtain line emissivities and ratios. A new extension of SPECTRA is to extend the atomic model to include level-specific ($e + ion$) recombination coefficients from accurate R-matrix calculations (Hoy *et al.* 2023, NORAD 2024). The extended collisional-radiative-recombination (CRR) model incorporates ($e + ion$) recombination to a number of excited levels, and radiative decays therefrom, into the upper levels that give rise to the observed forbidden lines.

2 OBSERVATIONAL DATA ANALYSIS

Spectral data for 30 galaxies observed with JWST/NIRSpec, ground-based observations of 5 galaxies from Keck/KCWI/NIRSPEC/MOSFIRE, 7 galaxies from VLT/Shooter, 1 galaxy from CLASSY, and 1 galaxy from MOSDEF was analyzed (see References). In addition, data from a few other ground-based instruments was also obtained from literature. Detailed information on data sources is given in Appendices [Table A1](#) and [Table A2](#), along with reported quantitative fluxes for [O III], [O II] and [S II] lines, as well as H \$\beta\$ fluxes.

The JWST line data in our collection are all from $z > 1$. For analyzing some galaxies for approximate comparison in the low- z region, we added a few galaxies from ground-based observations. The data used for lower redshift ground-based observations does not include all ground-based observations until the present epoch but a representative sample of a few points. For the galaxies that appears twice in the tables, they are analyzed using different sets of line fluxes data, as shown in [Table A1](#). The results are arranged in the same order when reproduced in [Table A3](#).

We collected the data for galaxies whose observed fluxes have been reported for determining spectral properties, namely unblended [O II] $\lambda 3729, \lambda 3726$ or unblended [S II] $\lambda 6717, \lambda 6732$ fine structure doublet formed by atomic structure and transitions $^4S^o - ^2D^o_{3/5,3}$ that are standard density diagnostics. The temperature diagnostic [O III] $\lambda 4363, \lambda 5007$ lines due to the atomic transitions $^1D_2 - ^1S_0$ and $^3P^o_2 - ^1D_2$ respectively, that have been identified and extracted until recently available observations.

There are several cases where there are some lines missing from papers in literature. However, our line ratios analysis attempts to estimate their intensities from theoretical line emissivity calculations described below. In particular, if [O III] $\lambda 4959$ is missing (necessary for the Oxygen abundance formula from Izotov *et al.* (2006)), we calculate its intensity since the ratio [O III] $\lambda 5007 / \lambda 4959 = 2.88$ is constant. That is because both transitions originate from the same upper level and the intensity ratio is determined by their respective A-values ?, and independent of environment temperature or density. In cases where [O II] $\lambda 3729, 3726$ lines are missing then we employ the [O II] $\lambda 7320, \lambda 7332$ lines due to forbidden transitions $2s^2p^3(^2D^o_{3/2} - ^2P^o_{1/2,3/2})$ (c.f. Izotov *et al.* 2006).

3 THEORY & COMPUTATIONAL METHOD AND ATOMIC DATA

The calculations described in this paper employ high-accuracy atomic data computed using the powerful R-matrix method and subsidiary codes described in this section. The CRR model includes atomic parameters discussed in the following subsections.

3.1 Energy Levels & Einstein A Coefficients

The energy level data for OIII is computed using the R-matrix method (Nahar 1998) but substituted using observed energies where available from the National Institute of Standards and Technology (NIST) Atomic Spectra Database (www.nist.gov). The transition probabilities and A-coefficients are also obtained from previous R-matrix calculations and archived in the database Nahar-OSU-Radiative-Atomic-Database (NORAD; <http://norad.astronomy.osu.edu>).

Fig. 1 shows the atomic model of OIII including the 10 well-known forbidden transitions among the 5 even-parity levels of the ground configuration $1s^22s^22p^2 : ^3P_{0,1,2}, ^1D_2, ^1S_0$. These levels are considered for collisional excitation. In addition, and for including ($e + ion$) recombination into higher levels and radiative cascades therefrom, excited electronic configurations up to $n = 10$ are included.

3.2 Electron Impact Excitation

We consider collision strengths and Maxwellian averaged rate coefficients for the forbidden [O III] ground configuration transitions as in earlier works (Palay *et al.* 2012, Storey and Sochi 2015). The two sets of data agree within a few per cent throughout most of the temperature range of interest in nebulae, but differ somewhat at low electron temperatures $T_e < 1000K$ where the latter are to be preferred. That is because Storey and Sochi (2015) include additional correlation in the wavefunction expansion for the [O III] levels that include the excited configuration $1s^22p^6$ that correlates with the quasi-degenerate 1S_0 level of the ground configuration $1s^22s^22p^2$. That additional correlation gives rise to somewhat lower resonance structures near the excitation thresholds up to the 1S_0 level, resulting Maxwellian averaged collision strengths that differ from Palay *et al.* (2012). However, as we show later, the line emissivity ratios in the range of interest herein is hardly affected in using the two sets.

3.3 Electron-ion recombination

In order to discern possible effects due to ($e + ion$) recombination, i.e. $(e + O iv) \rightarrow O iii$, we considerably expand the set of excited energy levels of O III. That enables recombination into excited levels followed by radiative cascades to the 5 levels that give rise to the observed forbidden lines via dipole allowed transitions down to upper levels. The CRR code uses the extensive datasets for level-specific ($e + ion$) recombination and A-values from the database NORAD ?needed to construct the radiative-cascade matrices. Contributions to upper level populations from ($e + ion$) recombination is then computed by SPECTRA code for particular [O II], [S II] and [O III] lines.

3.4 Line Emissivities & Ratios

The CRR model is incorporated in a code SPECTRA that computes line emissivities and diagnostic ratios from the data described above. There are two versions of SPECTRA in Fortran and C++ that have been compared against each other (Hoy *et al.* 2023).

The procedure adopted relies on the canonical [O III] $\lambda 5007/\lambda 4363$ line ratio that is known to be dependent on electron temperature, and the [O II] $\lambda 3729/\lambda 3726$ and [S II] $\lambda 6717/\lambda 6731$ line ratios that are sensitive to electron density. However, as we note below, there are two sets of [O III] theoretical collision strengths available in literature: Palay *et al.* (2012) and Storey and Sochi (2015). We compute and compare the two sets in Fig. 1a, and find little difference in the nebular temperature range under consideration (see section Electron Impact Excitation below). Using the later Storey and Sochi (2015) data, and [O II] and [S II] collision strengths, we construct a contour plot of the full electron temperature-density range shown in Fig. 1b.

4 RESULTS

Once the temperature and density are determined from line emissivities and observed line intensity ratios we may derive the oxygen abundance. For oxygen abundance calculations, we adopt two different empirical formulae by Izotov *et al.* (2006) and Méndez-Delgado *et al.* (2023) respectively.

4.1 Formula by Izotov *et al.* (2006)

Izotov *et al.* (2006) re-evaluated empirical expressions for abundance determination from spectral data from emission line galaxies using the Sloan Digital Sky Survey (SDSS) for several elements. The inputs for this formula are relative line fluxes to H β , N_e , and T_e . Firstly, it defines $t = 10^{-4}T_e([OIII])$ and $x = 10^{-4}N_e t^{-0.5}$. The following formulae are used in this work:

$$12 + \log(O^+/H^+) = \log\left(\frac{OII3727}{H\beta}\right) + 5.961 + \frac{1.676}{t} - 0.40 \log(t) - 0.034t + \log(1 + 1.35x) \quad (1)$$

$$12 + \log(O^+/H^+) = \log\left(\frac{OII7320 + OII7330}{H\beta}\right) + 6.901 + \frac{2.487}{t} - 0.483 \log(t) - 0.013t + \log(1 - 3.48x) \quad (2)$$

$$12 + \log(O^{2+}/H^+) = \log\left(\frac{OIII4959 + OIII5007}{H\beta}\right) + 6.200 + \frac{1.251}{t} - 0.55 \log(t) - 0.014t \quad (3)$$

OII3727 represents the total(blended) relative flux of [OII] $\lambda 3726$ and [OII] $\lambda 3729$ to H β . If OII3727 is available, we could use (1) to calculate the OII abundance. If OII3727 is not available, we could use [OII] $\lambda 7320$ and [OII] $\lambda 7330$ relative fluxes by (2) to calculate the OII abundance. Also, using (3) with [OIII] $\lambda 4959$ relative flux, [OIII] $\lambda 5007$ relative flux, and electron temperature, we can calculate OIII abundance. Once we have the abundance for singly ionized state(OII) and doubly ionized state(OIII), we can add them up as (4) to get the total oxygen abundance.

$$\frac{O}{H} = \frac{O^+}{H^+} + \frac{O^{2+}}{H^+} \quad (4)$$

For a specific galaxy PJ308-21, the original paper Decarli *et al.* (2024) gives neither [O II] $\lambda 3729+\lambda 3726$ nor [O II] $\lambda 7320+\lambda 7330$ fluxes for using Izotov *et al.* (2006) oxygen abundance formula (1) or (2) to calculate $12 + \log(O^+/H^+)$. We then assume three

different values for [O II] $\lambda 3729+\lambda 3726$ relative flux to H β : 0.5, 1.0, and 2.0. This assumption is based on the fact that most of other galaxies we examined have [O II] $\lambda 3729+\lambda 3726$ relative flux to H β around the range 0.5 to 2.0. Only the abundance formulae (1) from Izotov *et al.* (2006) are used with this assumed [O II] $\lambda 3729+\lambda 3726$ relative flux for PJ308-21, and density determination was done by using [S II] lines. We find that results under such assumption are quite similar, $12 + \log(O/H) = 7.99, 8.02$ and 8.07 respectively. The another result for PJ308-21, by using another oxygen abundance formula from Méndez-Delgado *et al.* (2023)(will be discussed in 4.3), is $12 + \log(O/H) = 7.95$, which is quite similar to the results by assuming [O II] $\lambda 3729+\lambda 3726$ flux relative to H β with using Izotov *et al.* (2006) oxygen abundance formula (1). The first result $12 + \log(O/H) = 7.99$ is then adopted in the abundance over temperature, redshift, and lookback time plots.

4.2 Formula by Méndez-Delgado *et al.* (2023)

Whereas Izotov *et al.* (2006) express the overall oxygen abundance in terms of temperature and density dependence of O II and O III (Eq. 1-3), Mendez-Delgado *et al.* (2023) have presented empirical relations for the estimation of temperature and metallicity taking account of temperature inhomogeneities in H II regions. They estimate temperature fluctuations via a factor t^2 as the deviation from a mean temperature T_0 , and derive the following expression for the oxygen abundance

$$12 + \log(O/H) = (-1.07 \pm 0.09) \times 10^{-4}T_0(H^+) + (9.44 \pm 0.08), \quad (5)$$

where T_0 is the average temperature of ionized gas, which we take to be $\approx T_e$ (O III) following Mendez-Delgado *et al.* (2023). This is justified even if $t^2 > 0$ when one considers temperatures obtained from recombination lines as $T_e([N\text{ ii}] 5755/6584) T_0$ (O II). That is because in the regions of low ionization the emission of H I recombination is essentially from the volume of O II where temperature inhomogeneities are negligible, or $t^2 \approx 0$.

4.3 Oxygen Abundance vs. Redshift and Lookback Time

Figs. 3 presents the results for O-abundance for all galaxies studied herein using both the Izotov *et al.* (2006) and Mendez-Delgado *et al.* (2023) empirical formulae given above, plotted against electron temperature and color coded according to redshift z . Fig. 4 shows the results of O/H vs. z and lookback time in Gyrs, with temperature shown in the color coded bar. The lookback time was calculated from redshifts by Astropy Planck18 instance of Flat Λ CDM cosmology. The results in Fig. 4 also show redshift ranges $0 < z < 1$ (blue), $1 < z < 3$ (purple), $3 < z < 6$ and $6 < z < 11$, superimposed on a linear best fit through the data.

5 MACHINE LEARNING ANALYSIS

To complement the direct abundance derivations, we employ machine learning techniques to identify patterns in the parameter space and quantify predictive relationships. Our analysis uses 45 galaxies with complete measurements of z , $T_e[\text{o III}]$, and $12+\log(O/H)$.

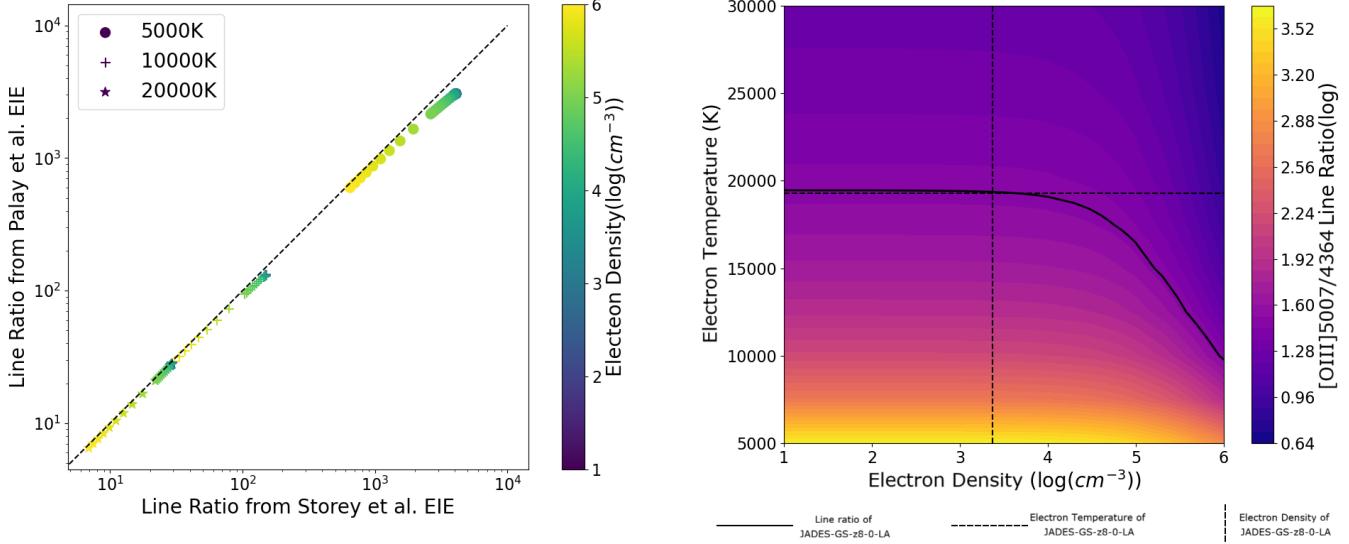


Figure 1. (Left a)Comparison between the [OIII] $\lambda 5007/\lambda 4363$ line ratio results of SPECTRA code by inputting [Storey & Sochi \(2015\)](#) and [Palay et al. \(2012\)](#) effective collisional strength data. (Right b)[OIII] $\lambda 5007/\lambda 4363$ line ratio contours results of SPECTRA code by inputting [Storey & Sochi \(2015\)](#) effective collisional strength data.

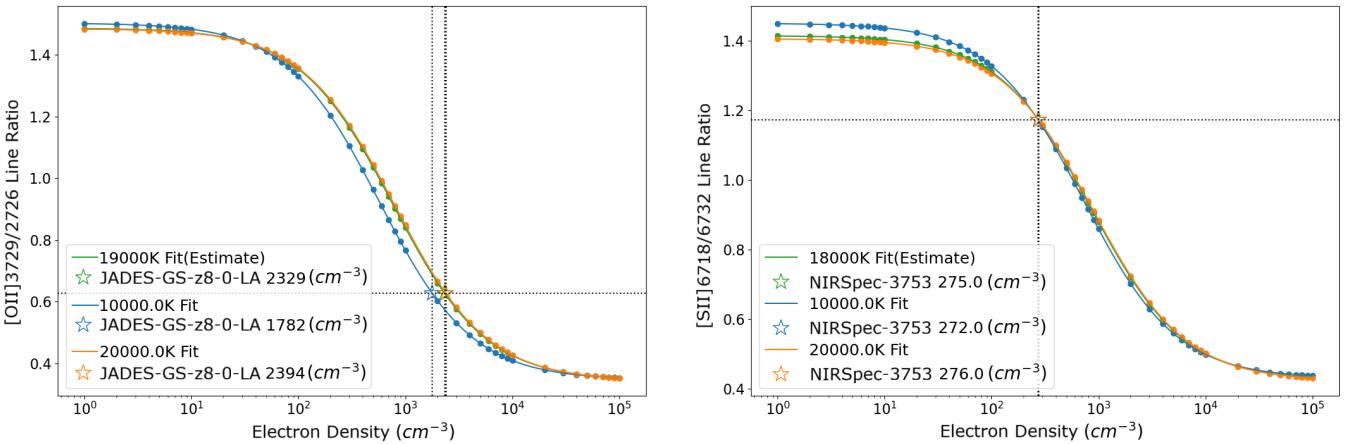


Figure 2. (Left a)[OII] $\lambda 3729/\lambda 3726$ Density Diagnostics. (Right b)[SII] $\lambda 6718/\lambda 6732$ Density Diagnostics.

5.1 K-Means Clustering

Employing the elbow method, we identify $k = 3$ as the optimal cluster number. The three clusters exhibit distinct physical characteristics (Fig. 8):

- **Cluster 0** (Local/Intermediate, $n = 17$): $\langle z \rangle = 1.39 \pm 1.58$, $\langle T_e \rangle = 10,953 \pm 1,120$ K, $\langle 12+\log(\text{O/H}) \rangle = 8.29 \pm 0.15$
- **Cluster 1** (Early Universe, $n = 10$): $\langle z \rangle = 6.18 \pm 2.65$, $\langle T_e \rangle = 17,960 \pm 1,336$ K, $\langle 12+\log(\text{O/H}) \rangle = 7.68 \pm 0.15$
- **Cluster 2** (High-Redshift, $n = 18$): $\langle z \rangle = 4.73 \pm 2.26$, $\langle T_e \rangle = 14,439 \pm 1,989$ K, $\langle 12+\log(\text{O/H}) \rangle = 8.02 \pm 0.13$

Analysis of variance confirms these clusters are statistically distinct ($F = 57.43$, $p < 0.001$), with post-hoc pairwise comparisons showing significant differences between all pairs ($p < 0.001$ after Bonferroni correction). The clustering naturally separates galaxies by cosmic epoch, with clear trends in both temperature and metallicity.

5.2 Predictive Regression Models

We evaluate four regression algorithms: Linear Regression, Ridge Regression ($\alpha = 1.0$), Random Forest, and Gradient Boosting, using z and T_e as predictors. Performance is assessed via 70-30 train-test split with 5-fold cross-validation.

Ridge Regression achieves optimal performance with $R^2 = 0.832$ (test set), RMSE = 0.128 dex, and MAE = 0.089 dex (Table 1). This substantially outperforms theoretical models fit to the same data: exponential ($R^2 = 0.311$) and power law ($R^2 = 0.324$), representing a $\sim 160\%$ improvement. The ensemble methods (Random Forest: $R^2 = 0.642$; Gradient Boosting: $R^2 = 0.328$) underperform likely due to the limited sample size.

The Ridge model predictions with 95% bootstrap confidence intervals (1000 iterations) are shown in Fig. 9. Residual analysis reveals no systematic trends with redshift (slope: -0.003 ± 0.008), confirming the model captures the functional form adequately. The 95% predic-

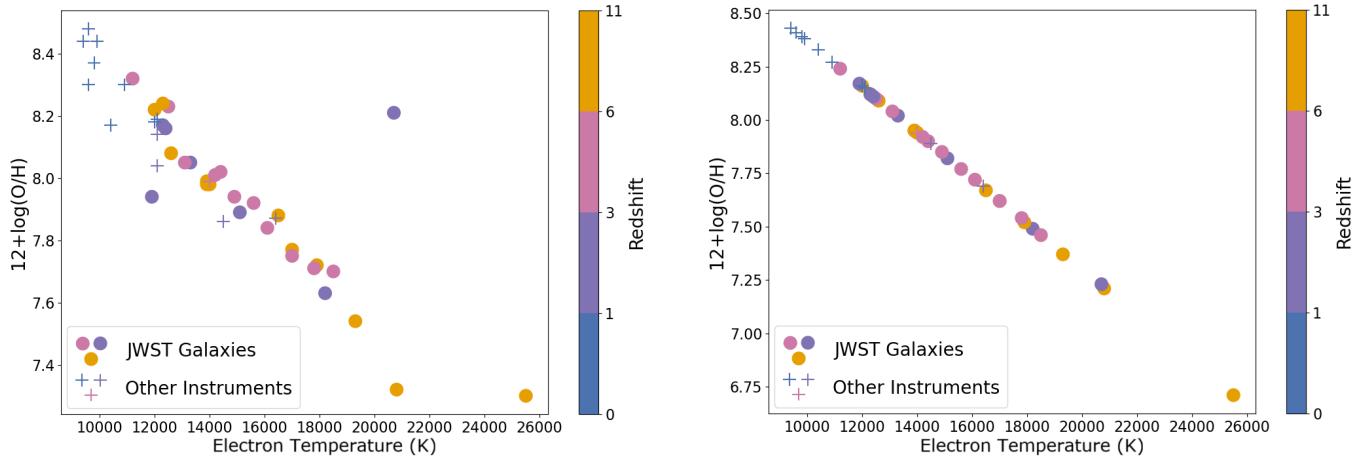


Figure 3. Oxygen Abundance Evolution with temperature using Izotov et al. (2006) formula (Left a) and Méndez-Delgado et al. (2023) formula (Right b)

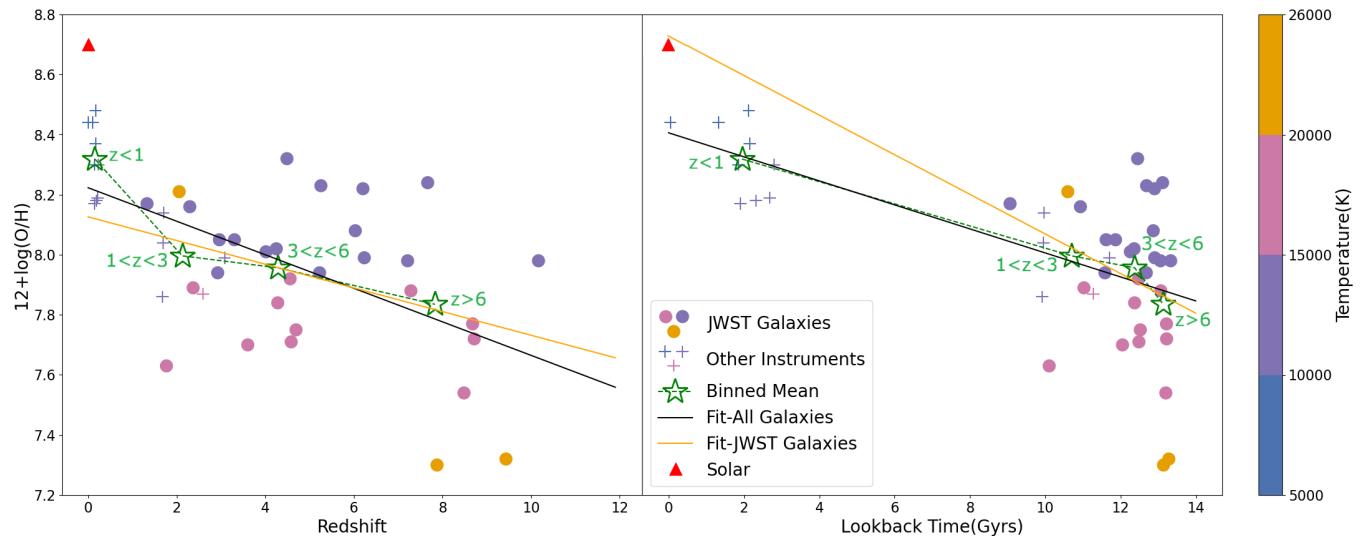


Figure 4. Oxygen abundance evolution with redshift (Left a) and lookback time (Right b) using Izotov et al. (2006) formula

Table 1. Regression model performance metrics.

Model	R^2 (test)	RMSE (dex)	MAE (dex)	R^2 (CV)
Linear Regression	0.832	0.128	0.089	0.34 ± 0.86
Ridge Regression	0.832	0.128	0.089	0.34 ± 0.86
Random Forest	0.642	0.186	0.110	0.18 ± 0.70
Gradient Boosting	0.328	0.255	0.131	-0.55 ± 1.42

Table 2. Redshift-binned oxygen abundance statistics.

Bin	n	$\langle z \rangle$	$12+\log(\text{O/H})$	$\langle T_e \rangle$ (K)
$z < 1$	9	0.15 ± 0.07	8.32 ± 0.12	$10,411 \pm 1,036$
$1 \leq z < 3$	11	2.13 ± 0.55	8.06 ± 0.26	$14,245 \pm 3,188$
$3 \leq z < 6$	14	4.25 ± 0.69	7.98 ± 0.22	$14,593 \pm 2,446$
$z \geq 6$	11	7.84 ± 1.36	7.88 ± 0.28	$15,545 \pm 2,929$

tion interval of ± 0.246 dex is comparable to typical measurement uncertainties.

5.3 Redshift-Binned Evolution

We partition the sample into four redshift bins and calculate weighted means (Table 2). The systematic decrease of $\Delta[12+\log(\text{O/H})] = 0.44$ dex from $z \sim 8$ to present corresponds to a factor of ~ 2.8 increase in absolute oxygen abundance. Linear regression on binned means yields a slope of -0.052 ± 0.012 dex per unit z ($p < 0.001$),

though the best-fit is better described by non-linear evolution approaching solar values asymptotically at $z \rightarrow 0$.

5.4 Physical Interpretation

The superior performance of the bi-variate Ridge model demonstrates that chemical evolution cannot be captured by redshift alone. The strong temperature-abundance anti-correlation ($r = -0.878$, $p < 0.001$) explains much of the scatter in z -abundance space, reflecting diverse ionization conditions and star formation histories among galaxies at fixed epochs. The systematic enrichment from

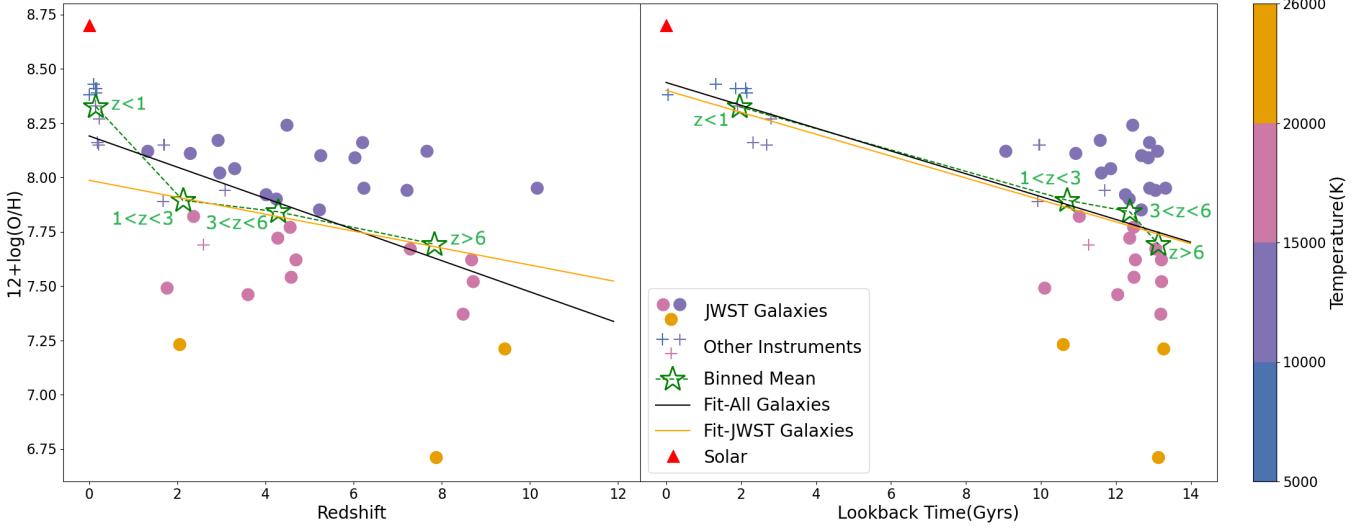


Figure 5. Oxygen abundance evolution with redshift (Left a) and lookback time (Right b) using Méndez-Delgado et al. (2023) formula

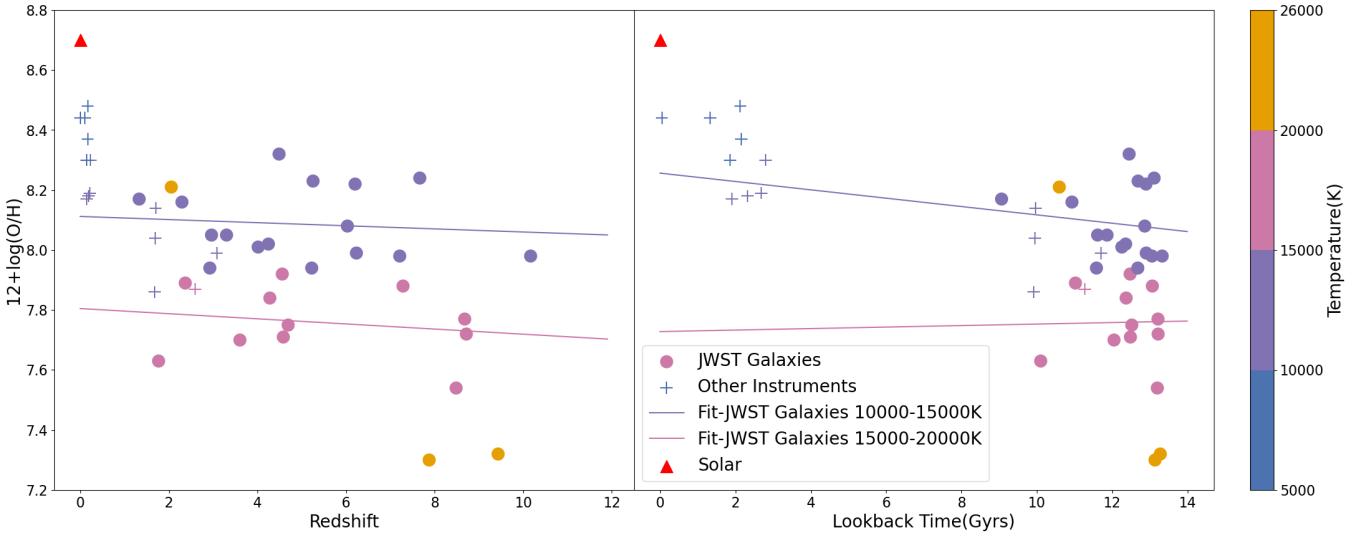


Figure 6. Oxygen abundance evolution with redshift (Left a) and lookback time (Right b) using Izotov et al. (2006) formula, with fitting to 10000-15000K and 15000-20000K temperature bins separately

$z \sim 10$ to present is consistent with hierarchical galaxy formation where progressive stellar nucleosynthesis enriches the ISM over cosmic time.

The ML approach validates our direct theoretical analysis while providing statistical quantification of uncertainties. The demonstrated predictive capability ($R^2 = 0.832$) suggests this methodology can enable rapid abundance estimation for large samples where full photoionization modeling is computationally prohibitive, valuable for upcoming wide-field surveys.

6 DISCUSSION

Broadly speaking, the results presented in the previous section demonstrate a decreasing trend in O/H with redshift as shown in Fig. 4 and 5. In each z -range selected for binning the large sample of

galaxies the downward trend is discernible overall. The decreasing pattern holds according to the best linear fits as well as averages in each z -binned range. However, there is marked difference in O-abundance relative to electron temperature. In fact, Fig. 4 exhibits a clear dichotomy between higher temperature JWST galaxies with significantly lower oxygen abundances, compared to those with lower temperatures. The scatter around the line of best linear fit is therefore a measure of uncertainty in the results. The machine learning analysis validates these trends statistically, with Ridge regression achieving $R^2=0.832$ and confirming the strong Te-abundance anti-correlation.

7 CONCLUSIONS

The main conclusion of the analysis presented in this paper is that there is a distinct and systematic trend in the decrease of oxygen

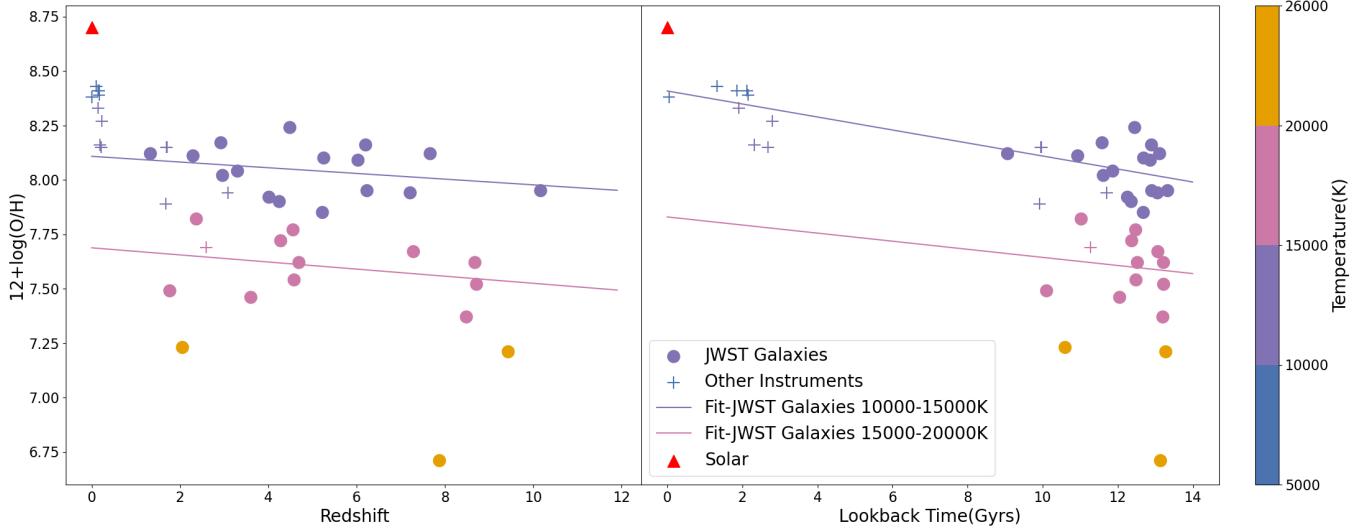


Figure 7. Oxygen abundance evolution with redshift (Left a) and lookback time (Right b) using Méndez-Delgado et al. (2023) formula, with fitting to 10000-15000K and 15000-20000K temperature bins separately

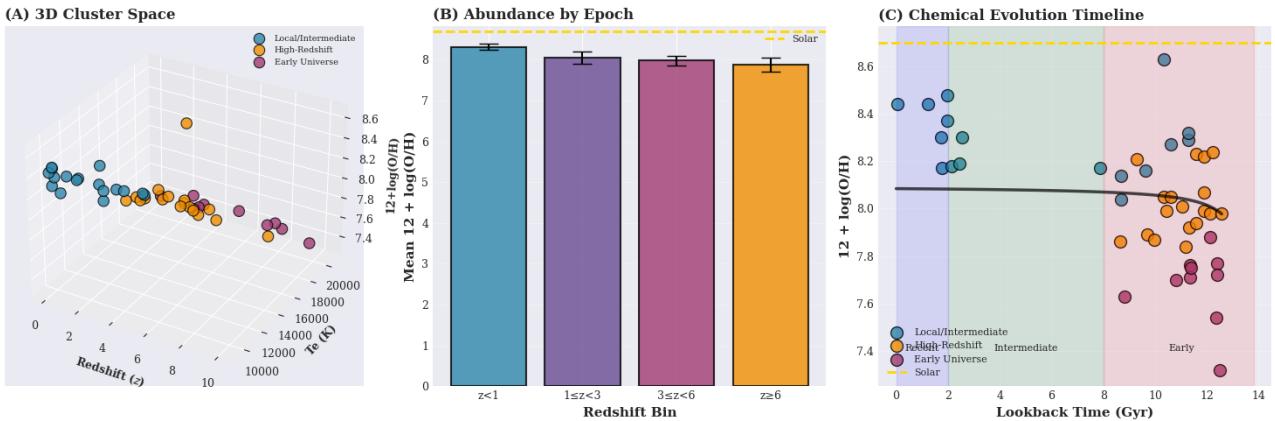


Figure 8. K-Means clustering results. *Left:* 3D parameter space showing three distinct clusters corresponding to cosmic epochs. *Center:* Mean oxygen abundance by redshift bin with 95% confidence intervals, demonstrating systematic evolution. *Right:* Chemical evolution timeline with lookback time, showing approach to solar abundance (gold dashed line) at low redshift. Shaded regions indicate cosmic epochs: Recent (blue), Intermediate (green), and Early (red) Universe.

abundance with increasing redshift up to $z > 10$. The analysis depended on a re-examination of line ratios of [O III] lines, together with [O II] and [S II] calculated line emissivities and observed line intensity ratios. Despite the scatter in derived parameters from a fairly large sample of galaxies, the overall trend and redshift-averaged values appear to lead to the same conclusion.

DATA AVAILABILITY

REFERENCES

ACKNOWLEDGEMENTS

This work applied the following PYTHON package: Astropy (Astropy Collaboration et al. 2013, Astropy Collaboration et al. 2018, and Astropy Collaboration et al. 2022), SciPy (Virtanen et al. 2020), Matplotlib (Hunter 2007), and NumPy (Harris et al. 2020).

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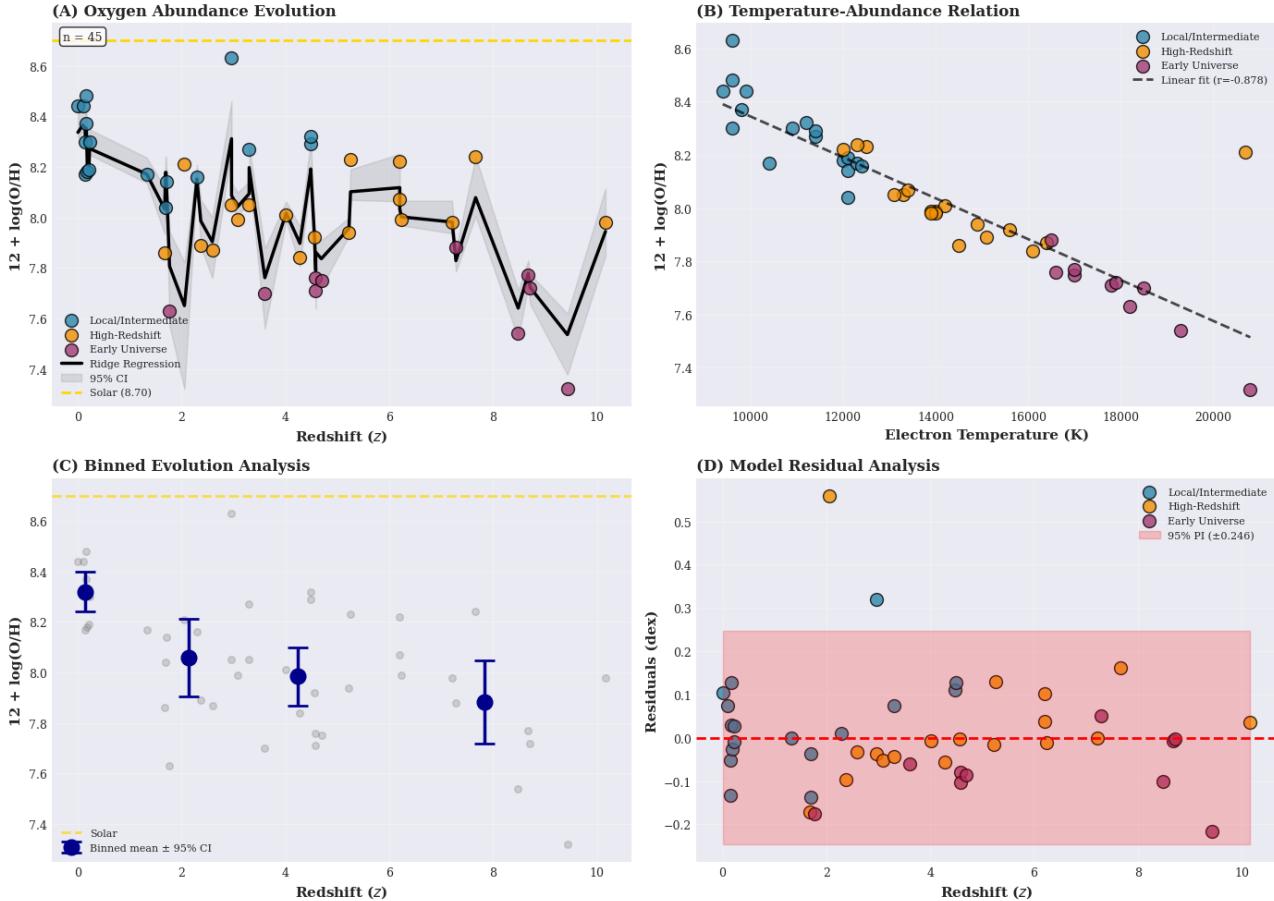


Figure 9. Machine learning regression analysis. (A) Oxygen abundance evolution with redshift, colored by cluster membership. Ridge regression prediction (black line) with 95% bootstrap confidence interval (gray shading). Solar abundance shown as gold dashed line. (B) Temperature-abundance relation demonstrating strong anti-correlation ($r = -0.878, p < 0.001$). (C) Binned evolution with error bars showing systematic enrichment (individual galaxies in gray). (D) Model residual analysis showing no systematic trends and 95% prediction interval (red shading, ± 0.246 dex).

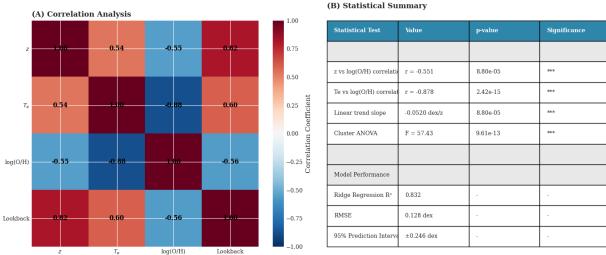


Figure 10. Statistical analysis summary. *Left:* Correlation matrix showing strong relationships between physical parameters. *Right:* Table of statistical tests demonstrating significance of observed trends (all $p < 0.001$) and model performance metrics.

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APPENDIX A: DATA COLLECTION OF ANALYSIS RESULTS AND LINE FLUXES FROM LITERATURE

Table A1. A holistic table of line fluxes from other papers. All line fluxes are normalized by H β = 1.

Galaxy	z	OII3726	OII3729	OIII4363	OIII4959	OIII5007	SII6718	SII6732	OII7320	OII7330	H β Flux ($erg\ s^{-1}\ cm^{-2}$)
Haro3	0.003208	1.243	1.577	0.02521	1.361	4.016	0.1461	0.1172	-	-	-
J0021+0052	0.09839	0.6407	0.7217	0.02202	1.537 ^c	4.427	0.1819	0.1312	0.02554	0.01982	2.271 · 10 ⁻¹⁴
J032845.99+011150.8	0.142181	2.154 ^a	-	0.01280	0.7333	2.294	0.2849	0.2191	0.02312	0.01920	2.812 · 10 ⁻¹⁵
J015028.39+130858.4	0.146712	2.220 ^a	-	0.01650	0.7424	2.221	0.2570	0.2205	0.01881	0.01568	6.059 · 10 ⁻¹⁵
J124509.05+104340.1	0.165569	1.775 ^a	-	0.02845	1.718	5.122	0.1714	0.1435	0.02856	0.02243	8.648 · 10 ⁻¹⁵
J005527.45-002148.7	0.167449	2.008 ^a	-	0.02228	1.236	3.673	0.1768	0.1573	0.03513	0.02718	1.611 · 10 ⁻¹⁴
J101629.88+073404.9	0.18271	2.271 ^a	-	0.05832	1.729	5.236	0.1475	0.1231	0.02264	0.01852	7.288 · 10 ⁻¹⁵
J082247.66+224144.0	0.216226	2.090 ^a	-	0.06771	1.924	5.814	0.1329	0.1225	0.03747	0.02757	8.994 · 10 ⁻¹⁵
J084034.10+134451.3	0.226961	1.785 ^a	-	0.04537	1.784	5.353	0.1842	0.1465	0.02768	0.02191	2.601 · 10 ⁻¹⁵
GOODS-N-14595	1.67596	0.5759	0.6161	0.08929	1.692	4.960	0.2500	<0.5446	-	2.240 · 10 ⁻¹⁷	-
GOODS-N-8240	1.6909	0.5944	0.6285	0.04954	1.458	4.434	<0.9659	<5.399	-	3.230 · 10 ⁻¹⁷	-
RCSGA032727-132609	1.7	1.133	0.9876	0.05637	1.543	4.900	0.1448	0.1066	-	4.495 · 10 ⁻¹⁵	-
SGAS1723-34	1.3293	-	-	0.07480	2.084	6.239	0.1447	0.1076	0.02103	0.01935	1.845 · 10 ⁻¹⁵
NIRSpec3753	1.768	2.692 ^a	-	0.1169	1.270	4.040	0.2770	0.2361	-	8.810 · 10 ⁻¹⁸	-
CEERS-3506	2.055	-	-	0.2350	2.530	6.510	0.01360	0.02230	0.007100	0.004200	2.210 · 10 ⁻¹⁷
CEERS-3788	2.295	0.4170	0.4590	0.08800	2.370	7.010	0.3720	0.2330	-	-	-
Sunburst Arc	2.37	0.2900	0.2200	0.1380	2.200	6.800	0.03900	0.04300	0.03000	0.02200	6.600 · 10 ⁻¹⁹
A1689-217	2.5918	1.156	1.339	0.1094	2.156	6.210 ^c	-	-	-	1.920 · 10 ⁻¹⁶	-
SGAS1226+21	2.925	-	-	<0.04707	1.320	4.327	0.3045	0.2917	<0.006973	<0.006973	1.721 · 10 ⁻¹⁶
Q2343-D40	2.963	-	-	0.08700	1.993	5.914	0.1310	0.09700	0.02500	0.02000	8.650 · 10 ⁻¹⁸
Q2343-D40	2.963	-	-	0.04000	2.254	7.075	0.1310	0.09700	0.02500	0.02000	-
COSMOS-1908	3.08	0.2309	0.2509	0.1186	2.288	7.055	-	-	-	4.720 · 10 ⁻¹⁷	-
CEERS-11088	3.302	1.681 ^a	-	0.05737	2.041	6.052	0.2147	0.1714	0.07257 ^b	-	2.632 · 10 ⁻¹⁷
CEERS-11088	3.302	0.5200	0.4700	0.08800	1.936	6.233	0.5830	0.2570	-	-	-
JADES-19519	3.604	0.3790	0.5330	0.2010	2.279	6.782	-	-	-	-	-
GLASS-160133	4.015	0.2140	0.2610	0.1540	2.559	7.725	-	-	-	-	-
GTO1199-150880	4.247	1.006 ^a	-	0.1358	10.26 ^d	-	0.08447	0.06849	-	-	8.760 · 10 ⁻¹⁸
GRB050505	4.28	0.7037	0.9722	0.1389	2.065	6.046	0.2778	0.2037	-	-	1.080 · 10 ⁻¹⁷
CEERS-1665	4.482	1.514 ^a	-	0.06532	2.214	6.827	0.1512	0.1243	<0.08772 ^b	-	2.679 · 10 ⁻¹⁷
CEERS-1665	4.488	0.5120	0.3520	0.06700	2.338	7.336	0.3100	0.2030	-	-	-
CEERS-1746	4.56	1.120 ^a	-	0.1624	2.251	7.604	0.09117	0.09687	<0.1425 ^b	-	3.510 · 10 ⁻¹⁸
GLASS-150029	4.584	0.1780	0.2070	0.1840	2.328	6.588	-	-	-	-	-
GLASS-150029	4.584	0.1827	0.2373	0.1530	2.221	6.316	-	-	-	-	8.230 · 10 ⁻¹⁸
ID60001	4.6928	0.5650 ^a	-	0.1640	2.170	6.470	0.04374	0.03645	-	-	4.054 · 10 ⁻¹⁸
EXCELS-121806	5.225	0.8411 ^a	-	0.1339	2.327	6.826	0.05920	0.04835	-	-	2.564 · 10 ⁻¹⁸
EXCELS-70864	5.255	0.8541 ^a	-	0.1108	2.854	8.617	<0.03900	<0.04446	-	-	-
J1211-0118	6.031	0.9760	1.163	<0.06200	1.605	4.783	-	-	-	-	1.260 · 10 ⁻¹⁷
J0217-0208	6.204	0.8930	0.6030	0.07500	2.004	6.567	-	-	-	-	1.880 · 10 ⁻¹⁷
J0217-0208	6.204	0.8930	0.6030	0.05952	2.234 ^c	6.433	0.08931	0.09482	-	-	9.070 · 10 ⁻¹⁸
PJ308-21	6.2342	0.510/2.0 ^{a,c}	-	0.1139	2.293	6.873	0.1418	0.1721	-	-	1.650 · 10 ⁻¹⁷
SXDF-NB1006-2	7.212	0.2660	0.2390	0.1130	2.262	6.741	-	-	-	-	8.550 · 10 ⁻¹⁹
GLASS-10021	7.286	0.3378	0.4730	0.1980	2.696	8.284	-	-	-	-	7.400 · 10 ⁻¹⁸
ERO6355	7.6651	0.5104	0.3896	0.1000	2.660	8.290	-	-	-	-	2.110 · 10 ⁻¹⁸
ZD12	7.8762	0.3300	0.2791	0.2559	7.051 ^d	-	-	-	-	-	6.090 · 10 ⁻¹⁹
JADES-GS-z8-0-LA	8.48523	0.1402	0.08785	0.1776	1.836	5.470	-	-	-	-	3.210 · 10 ⁻¹⁹
CEERS-1019	8.6791	0.2084	0.1781	0.1780	2.262	7.011	-	-	-	-	1.017 · 10 ⁻¹⁷
JADES-GS-z8-1-LA	8.71523	0.2667	0.2309	0.2010	2.401	7.153	-	-	-	-	8.360 · 10 ⁻¹⁹
JADES-GS-29-0	9.4327	0.07825	0.07294	0.1790	1.756	4.955	-	-	-	-	7.540 · 10 ⁻¹⁹
MACS0647-JD1	10.167	0.1038	0.07022	0.1130	2.396 ^c	6.900	-	-	-	-	3.275 · 10 ⁻¹⁸

^aThis is the blended flux for OII3726+OII3729.^bThis is the blended flux for OII7320+OII7330.^cThis is not come from papers, it is come from assumptions as shown in the text of Appendix A^dThis is the blended flux for OIII4959+OIII5007.

Table A2. Line flux data sources of galaxies

Source	Instrument	Adopted line flux data of galaxies
Acharyya et al. (2019)	Keck/NIRSPEC	All data of RCSCA032727-132609.
Chen et al. (2024)	Keck/KCWI	All data of Haro3.
Clarke et al. (2023)	Keck/MOSFIRE	All data of GOODS-N-14595 and GOODS-N-8240.
Loaiza-Agudelo et al. (2020)	VLT/XShooter	All data of J032845.99+011150.8, J015028.39+130858.4, J124509.05+104340.1, J005527.45–002148.7, J101629.88+073404.9, J082247.66+224144.0, and J084034.10+134451.3.
Mingozzi et al. (2022)	CLASSY	All data of J0021+0052.
Sanders et al. (2016)	MOSDEF	All data of COSMOS-1908.
Arellano-Córdova et al. (2025)	JWST/NIRSpec	All data of EXCELS-121806 and EXCELS-70864.
Bhattacharya et al. (2025)	JWST/NIRSpec	All data of CEERS-3788, the second row of CEERS-11088, the first row of GLASS-150029, JADES-19519, and the second row of CEERS-1665. OIII4363, OIII4960, and OIII5008 line fluxes of the second row of Q2343-D40.
Decarli et al. (2024)	JWST/NIRSpec	All data of PJ308-21.
Harikane et al. (2025)	JWST/NIRSpec	All data of J1211-0118, SXDF-NB1006-2, and first row of J0217-0208. Line fluxes of OII 3726 and 3729 lines of the second row of J0217-0208
Sanders et al. (2023)	JWST/NIRSpec	Blended line flux of OII 3726 and 3729 lines and all other line flux data of CEERS-1019. All data of CEERS-1746, the first row of CEERS-11088, and the first row of CEERS-1665.
Isobe et al. (2023)	JWST/NIRSpec	OII 3726 and 3729 lines ratio of CEER-1019, ERO6355, GLASS-160133, and the second row of GLASS-150029.
Curti et al. (2022)	JWST/NIRSpec	Blended flux of OII 3726 and 3729 lines and all other line flux data of ERO6355.
Hsiao et al. (2025)	JWST/NIRSpec	Line flux OIII 5007($=226 \cdot 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-2}$) of MACS0647-JD1.
Hsiao et al. (2024)	JWST/NIRSpec	OIII5007/Hbeta($=6.9$) ratio of MACS0647-JD1.
Abdurro'uf et al. (2024)	JWST/NIRSpec	OII3726, OII3729, and OIII4363 line fluxes of MACS0647-JD1.
Welch et al. (2024)	JWST/NIRSpec	All data of SGAS1226+21 and SGAS1723+34.
Welch et al. (2025)	JWST/NIRSpec	All data of Sunburst Arc.
Matsuoka et al. (2025)	JWST/NIRSpec	All data except for fluxes of OII 3726 and 3729 lines of the second row of J0217-0208.
Rogers et al. (2024)	JWST/NIRSpec	All data of the first row of Q2343-D40. SII6718, SII6732, OII7320, and OII7330 line fluxes of the second row of Q2343-D40.
Nakajima et al. (2023)	JWST/NIRSpec	Blended line flux of OII 3726 and 3729 lines and all other line flux data of the second row of GLASS-150029, GLASS-10021, and GLASS-160133.
Curti et al. (2025)	JWST/NIRSpec	All data of JADES-GS-z9-0.
Witstok et al. (2024)	JWST/NIRSpec	All data of JADES-GS-z8-1-LA and JADES-GS-z8-0-LA.
Zhu et al. (2025)	JWST/NIRSpec	All data of CEERS-3506
Gburek et al. (2019)	Keck/MOSFIRE	All data of A1689-217.
Bunker et al. (2024)	JWST/NIRSpec	All data of NIRSpec3753.
Inkenhaag et al. (2025)	JWST/NIRSpec	All data of GRB050505.
Li et al. (2025)	JWST/NIRSpec	OII 3726 and 3729 lines ratio of GLASS-10021.
Morishita et al. (2025)	JWST/NIRSpec	All data of ZD12.
Stiavelli et al. (2024)	JWST/NIRSpec	All data of GTO1199-150880.
Zhang et al. (2025)	JWST/NIRSpec	All data of ID60001.

Table A3. A holistic table of analysis results by using [Storey & Sochi \(2015\)](#) EIE data

Galaxy	Instrument	z	12 + log(O/H) Izotov Formula	12 + log(O/H) MD Formula ^d	12 + log(O/H) Original Paper	$T_e[OIII]$ (K)	$N_e[OII]$ (cm^{-3})	$N_e[SII]$ (cm^{-3})
Haro3	Keck/KCWI	0.003208	8.44	8.38	8.309	9900	145	183
J0021+0052	CLASSY	0.09839	8.44	8.43	8.17 ^e	9400	275	50
J032845.99+011150.8	VLT/XShooter	0.142181	8.30	8.41	8.30	9600	-	126
J015028.39+130858.4	VLT/XShooter	0.146712	8.17	8.33	8.30	10400	-	283
J124509.05+104340.1	VLT/XShooter	0.165569	8.48	8.41	8.54	9600	-	245
J005527.45–002148.7	VLT/XShooter	0.167449	8.37	8.39	8.47	9800	-	343
J101629.88+073404.9	VLT/XShooter	0.18271	8.18	8.16	8.33	12000	-	239
J082247.66+224144.0	VLT/XShooter	0.216226	8.19	8.15	8.39	12100	-	412
J084034.10+134451.3	VLT/XShooter	0.226961	8.30	8.27	8.37	10900	-	170
SGAS1723+34	JWST/NIRSpec	1.3293	8.17	8.12	8.13	12300	-	80
GOODS-N-14595	Keck/MOSFIRE	1.67596	7.86	7.89	>7.62	14500	391	-
GOODS-N-8240	Keck/MOSFIRE	1.6909	8.04	8.15	8.02	12100	377	-
RCSGA032727-132609	Keck/NIRSPEC	1.7	8.14/8.13 ^a	8.15	8.19	12100	726	68
NIRSpec3753	JWST/NIRSpec	1.768	7.63	7.49	-	18200	-	275
CEERS-3506	JWST/NIRSpec	2.055	8.21	7.23	7.52	20700	-	3755
CEERS-3788	JWST/NIRSpec	2.295	8.16	8.11	7.91	12400	320	-
Sunburst Arc	JWST/NIRSpec	2.37	7.89	7.82	7.97	15100	1196	870
A1689-217	Keck/MOSFIRE	2.5918	7.87	7.69	8.06	16400	284	-
SGAS1226+21	JWST/NIRSpec	2.925	>7.94	>8.17	>8.04	<11900	-	489
Q2343-D40	JWST/NIRSpec	2.963	8.05	8.02	8.07	13300	-	73
Q2343-D40	JWST/NIRSpec	2.963	8.63	8.41	8.01 ^f	9600	-	80
COSMOS-1908	MOSDEF	3.08	7.99	7.94	8.00	14000	491	-
CEERS-11088	JWST/NIRSpec	3.302	8.27	8.22	8.33	11400	-	175
CEERS-11088	JWST/NIRSpec	3.302	8.05	8.04	7.87 ^f	13100	668	-
JADES-19519	JWST/NIRSpec	3.604	7.70	7.46	7.48	18500	58	-
GLASS-160133	JWST/NIRSpec	4.015	8.01	7.92	7.95 ^g	14200	204	-
GTO1199-150880	JWST/NIRSpec	4.247	8.02	7.90	8.00	14400	-	195
GRB050505	JWST/NIRSpec	4.28	7.84	7.72	7.80	16100	73	53
CEERS-1665	JWST/NIRSpec	4.482	8.29	8.22	8.27	11400	-	217
CEERS-1665	JWST/NIRSpec	4.488	8.32	8.24	8.13	11200	1405	-
CEERS-1746	JWST/NIRSpec	4.56	7.92	7.77	7.95	15600	-	766
GLASS-150029	JWST/NIRSpec	4.584	7.71	7.54	7.53	17800	294	-
GLASS-150029	JWST/NIRSpec	4.584	7.76	7.66	7.70 ^g	16600	143	-
ID60001	JWST/NIRSpec	4.6928	7.75	7.62	7.75	17000	-	236
EXCELS-121806	JWST/NIRSpec	5.225	7.94	7.85	7.97	14900	-	205
EXCELS-70864	JWST/NIRSpec	5.255	8.23	8.10	8.21	12500	-	~961 ^c
J1211-0118	JWST/NIRSpec	6.031	>8.08	>8.09	8.51	<12600	226	-
J0217-0208	JWST/NIRSpec	6.204	8.22	8.16	8.20	12000	1526	-
J0217-0208	JWST/NIRSpec	6.204	8.07	8.01	-	13400	-	743
PJ308-21	JWST/NIRSpec	6.2342	7.99/8.02/8.07 ^b	7.95	-	13900	-	1206
SXDF-NB1006-2	JWST/NIRSpec	7.212	7.98	7.94	7.99	14000	701	-
GLASS-10021	JWST/NIRSpec	7.286	7.88	7.67	7.87 ^g	16500	61	-
ERO6355	JWST/NIRSpec	7.6651	8.24	8.12	8.24 ^h	12300	1074	-
ZD12	JWST/NIRSpec	7.8762	7.30	6.71	7.34	25500	1007	-
JADES-GS-z8-0-LA	JWST/NIRSpec	8.48523	7.54	7.37	7.481	19300	2329	-
CEERS-1019	JWST/NIRSpec	8.6791	7.77	7.62	7.78 ⁱ	17000	893	-
JADES-GS-z8-1-LA	JWST/NIRSpec	8.71523	7.72	7.52	7.699	17900	885	-
JADES-GS-z9-0	JWST/NIRSpec	9.4327	7.32	7.21	7.41	20800	743	-
MACS0647-JD1	JWST/NIRSpec	10.167	7.98	7.95	7.79 ^j	13900	1613	-

^aLeft value is calculated by using $N_e[OII]$, and the right is by using $N_e[SII]$. Other galaxies with using both OII and SII electron density give same electron temperature and oxygen abundance, so they are just listed as one electron temperature and oxygen abundance value.

^bFrom 3 assumptions of OII3726+OII3729 flux 0.5/1.0/2.0 respectively

^cUpper limit of both SII lines are used to get the line ratio, so it is a uncertain value.

^dMéndez-Delgado Formula. The uncertainty of 12 + log(O/H) derived by this formula for all galaxies is about 0.2.

^e([Berg et al. 2022](#))

^f([Bhattacharya et al. 2025](#))

^g([Nakajima et al. 2023](#))

^h([Curti et al. 2022](#))

ⁱ([Sanders et al. 2023](#))

^j([Hsiao et al. 2024](#))