The importance of abundance ratios in interpreting high-z emission line spectra

Dan Masters (IPAC/JPL)
+Andreas Faisst, Peter Capak

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The Local "BPT" diagram
High-z galaxies *systematically* offset in O3N2
Local analogs

- A (rare) population of local galaxies exists that is remarkably similar in global properties to the high-redshift samples
  - E.g., the “green peas” (Cardamone et al. 2010)
  - Occupy same part of O3N2 diagram as high-z samples, with enhanced sSFRs & ionization parameters (Bian et al. 2016)

From Bian et al. 2016
Use empirical correlations in O3N2

- Examine how measurable physical properties of SDSS galaxies correlate with position on the diagnostic diagram
  - SDSS data has the advantage of S/N and statistical power, contains numerous “analogs” to high-z galaxies
- Assume the same factors that cause local analogs to be offset in the O3N2 diagram drive the observed shift at high redshift

SFR density and stellar mass in O3N2

\[ \Sigma_{\text{SFR}} \propto \frac{L(H\alpha)}{R_{\text{eff}}^2} \]

\[ \log(M_\odot) \]

Local relation
- z~2.3 relation (Steidel et al. 2014)

Fixed ionization parameter
[OIII]/Hβ closely linked to ionization parameter over most of the diagram
Putting it together

$$\Sigma_{\text{SFR}} \propto \frac{L(H\alpha)}{R_{\text{eff}}^2}$$

Interpretation

- Evolving BPT locus reflects changing mass-metallicity relation, which in turn reflects higher global SFR at high redshift
- But why does the position of the locus shift? Why don’t galaxies just move along the BPT locus with decreasing metallicity?
No shift in diagrams not involving N

BPT diagram is sensitive to the N/O ratio

- N/O ratio directly impacts where galaxies fall on the x axis of the BPT diagram

Van Zee et al. 1998
N/O ratio and stellar mass are distributed similarly across most of the diagnostic diagram, spanning a range of metallicities, SFRs, and ionization states – strong evidence that N/O-mass relation is more fundamental than N/O-metallicity.
A quick aside on E(B-V)

E(B-V) from Balmer decrement shows a similar fundamental correlation with stellar mass, as also noted by Garn & Best 2010
At fixed [OIII]/Hβ, moving toward the high-z locus is associated with both higher stellar mass and N/O ratio.
Why is N/O linked to mass?

- N/O ratio insensitive to inflows of H
  - Mostly insensitive to metal outflows as well
- O/H, in contrast, depends strongly on inflows
- Stellar mass of a galaxy is a rough measure of the past integral of chemical production through multiple stellar generations
  - N/O can be thought of as a marker of chemical maturity
  - Increases with secondary production of nitrogen through CN cycling in intermediate and massive stars
Conclusions

- Redshift evolution of line ratios in the BPT diagram arises naturally as a result of the evolution of the galaxy mass-metallicity relation
- Abscissa of BPT diagram ([NII]/Hα) is sensitive to stellar mass through its effect on the nitrogen-to-oxygen (N/O) abundance ratio
- N/O ratio is more fundamentally linked to stellar mass than to metallicity
- Nitrogen-based metallicity indicators should be viewed with caution – sensitive to N/O and hence mass
- Generally: galaxies with the same O/H at different redshifts are not the same
Implications for the Local FMR

A “fundamental metallicity relation” (FMR) has been proposed between mass, metallicity, and star formation rate (e.g., Mannucci 2010)

Top: Using new N/S-based metallicity calibration from Dopita et al. 2016 (primarily using the N/S ratio to measure metallicity)

Bottom: Using metallicity calibrations from Mannucci et al. 2010

The local FMR will appear weaker or absent when using nitrogen-based metallicity calibrations

From Kashino et al. 2016, “Hide-and-Seek with the Fundamental Metallicity Relation”
Dissecting the BPT diagram

- Examine how four measurable galaxy physical properties correlate with position in the O3N2 diagnostic diagram:

  1. $\Sigma_{\text{SFR}}$, using the proxy $L(\text{H}\alpha)/R_{\text{eff}}^2$
  2. Ionization parameter, from $[\text{NeIII}] \lambda 3869/[\text{OII}] \lambda \lambda 3726,3729$ (Levesque & Richardson 2014)
  3. N/O ratio, from the dust-corrected ratio $[\text{NII}]\lambda 6584/[\text{OII}]\lambda \lambda 3726,3729$
  4. Stellar mass

- $\sim 100,000$ galaxies from SDSS used for this analysis
  - See Masters, Faisst & Capak 2016 for details
Dependence of N/O vs. O/H on sSFR

- The local N/O vs. O/H relation is found to have a strong secondary dependence on sSFR (e.g., Brown et al. 2016)
- N/O-mass relation does not show such a secondary dependence on sSFR

From Brown et al. 2016
N/O-M_* relation + MZ evolution = BPT shift

High-z shift can be explained similarly

![Graph showing the relationship between log M_* (M_☉) and 12+log(O/H) for z~0 and z~2 relations, with a shift in N/O at fixed O/H.](image-url)
Mass in the BPT diagram at low/high-z

Measurements at $z \sim 2.3$ from KBSS (Steidel et al. 2014)
Summary of physical interpretation

- At fixed mass at high redshift, metallicity is lower and ionization parameter is higher (evolution of the MZ relation)
  \[ \rightarrow \text{Elevated } [\text{OIII}]/H\beta \text{ at fixed mass} \]
- At fixed [OIII]/H\beta at high redshift, both N/O ratio and stellar mass are higher
  \[ \rightarrow \text{Elevated } [\text{NII}]/H\alpha \text{ at fixed } [\text{OIII}]/H\beta \text{ ratio / metallicity} \]

The O3N2 shift can be viewed as a consequence of the evolution of the mass-metallicity relation combined with the link between stellar mass and relative nitrogen abundance.
Some evolution of the N/S-mass relation with redshift is observed, but not as much as would be expected from evolution of MZ relation if the N/O-O/H relation were invariant.
Nitrogen is produced in CNO burning in intermediate and high mass stars.

Which stars most effectively return nitrogen to the ISM and the relevant timescales are key uncertainties.

Extensive literature on the subject going back decades.

Implications for metallicity calibrations

- Metallicity calibrations involving nitrogen depend on the scaling of N/O with O/H
- An N/O-mass relation implies that these calibrations are sensitive to *stellar mass* in addition to instantaneous gas-phase metallicity

![Graph showing metallicity calibrations](image)

Right: The z~2 MZ relation from Cullen et al. 2014 using calibration based on [OII], [OIII], and Hβ, compared with Erb et al. 2006 using [NII]/Hα
Diagnostics involving stellar mass evolve as well

This strong evolution in the O32 vs. mass diagram shows that high-z galaxies at a given mass have much higher ionization parameters than low-z counterparts.

From Sanders et al. 2016