Chemical evolution of galaxies through cosmic time revealed with SPICA

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Optical measurements of metallicity of galaxies

- temperature method (using very faint lines)
  
  \[ \text{[OIII]4363} \rightarrow T_e \rightarrow \frac{(O^+ + O^{2+})}{H^+} \rightarrow O/H \]

  reliable, but very expensive

- strong-line method (models + calibration in low-z)
  
  \[ \frac{([\text{OII}]+[\text{OIII}])}{H\beta}, \frac{[\text{NII}]}{H\alpha}, \frac{[\text{NeIII}]}{[\text{OII}]}, \text{etc...} \]

  convenient, but should be used carefully

Mass-metallicity relation (MZR) of galaxies

More massive galaxies have a higher metallicity; “mass-metallicity relation (MZR)”.

MZR may be attributed to the younger nature, shallower gravitational potential, or stronger inflow/outflow in less-massive galaxies, or alternatively the mass dependence of the stellar IMF, or combination of these factors.

Anyway statistical properties of the metallicity such as MZR will give strong constraints on galaxy evolutionary models.

E.g., Lequeux et al. (1979), Tremonti et al. (2004), Lee et al. (2006), Panter et al. (2008), Kewley & Ellison (2008), Michel-an sac et al. (2008), Cooper et al. (2008), Ellison et al. (2009), Zahid et al. (2012), Foster et al. (2012), Andrews & Martini (2013), Kirby et al. (2013), Sanchez et al. (2013), Peng & Maiolino (2014), Gonzalez Delgado et al. (2014), Lian et al. (2015); see also Koppen et al. (2007), Finlator & Dave (2008) as theoretical studies.
Statistical evolution of metallicity in galaxies

MZR of galaxies evolves during the cosmological timescale (metallicity is lower at higher-z).

There seems to be a tendency that the more massive galaxies have chemically matured at the earlier epoch in the Universe, but other parameters (e.g., SFR) may affect the MZR and its evolution.

This is just an example; metallicity of galaxies (and its redshift evolution) gives us various insightful information about the galaxy evolution.

E.g., Savaglio et al. (2005), Erb et al. (2007), Maiolino, Nagao, et al. (2008), Hayashi et al. (2009), Mannucci et al. (2009), Lamareille et al. (2009), Calura et al. (2009), Perez-Montero et al. (2009), Yoshikawa et al. (2010), Sommariva et al. (2012), Yabe et al. (2012), Wuyts et al. (2012), Lara-Lopez et al. (2013), Zahid et al. (2014), Maier et al. (2014), Sanders et al. (2015); see also Ma et al. (2016), Torrey et al. (2019) as theoretical studies.
A major concern: many galaxies are “obscured”

Cosmic SFR density is dominated by LIRGs at $z > 0.5$, and it is dominated by ULIRGs at $z > 1.5$.

Except for low-$z$ Universe ($z < 0.5$), the star formation mostly occurred in IR-luminous, dusty galaxies (thus “obscured”).

For such galaxies, rest-frame optical spectra cannot study the ISM inside the galaxy properly; optical spectra just see their outer part, that may not be representative of those galaxies.

E.g., Le Floc’h et al. (2005), Caputi et al. (2007), Magnelli et al. (2009), Goto et al. (2010), Seymour et al. (2010), Rodighiero et al. (2010), Magnelli et al. (2011), Goto et al. (2011), Casey et al. (2012), Magnelli et al. (2013), Coppin et al. (2015), Goto et al. (2015), Toba, Nagao, et al. (2015); see also Bethermin et al. (2011) as a theoretical study.
Mass-metallicity relation of IR-selected galaxies

Metallicity of LIRGs and ULIRGs measured with optical diagnostics is lower than the expectation from MZR.

Does this mean that LIRGs and ULIRGs are chemically younger than IR-faint galaxies? Or, are we seeing only their optically-thin outer parts because of the heavy obscuration?
Another concern: ISM properties may evolve

Typical gas density in galaxies may be higher at higher-z. Maybe it is related to more intense SF activity at high redshift.

Moreover, ISM properties in heavily obscured part is unclear...
Thus it is unclear whether the “strong-line method” works well.

E.g., Masters et al. (2014), Shirazi et al. (2014), Shimakawa et al. (2015), Sanders et al. (2016), Onodera et al. (2016), Kaasinen et al. (2017); Kashino et al. (2017), Foster Schreiber et al. (2019); see also Araki, Nagao, et al. (2012) for high gas density in AGN host galaxies at high-z
Metallicity in AGNs: no evolution up to $z \sim 6-7$

Emission-line spectra of quasars look identical up to $z \sim 7$, suggesting that there is no significant metallicity evolution.

Is this consistent to the metallicity evolution of galaxies?

Most actively-evolving phase of AGNs is obscured by dust; thus we need to assess the obscured phase to study the chemically-growing phase of AGN host galaxies.
What we should do in the next step

- What we want to do
  - measuring the metallicity even for *obscured* galaxies and AGNs
  - investigating *also ISM physical properties* (such as the gas density) simultaneously

- What we need
  - diagnostic emission-line spectra at *long wavelengths*
  - with *various ionization status, critical density, ...*

→ Fine-structure lines (FSLs) in mid-IR and far-IR
Fine-structure lines (FSLs) from galaxies/AGNs

Grotrian diagram for [OIII]

Mid-IR FSLs viewed with Spitzer

Spitzer/IRS spectra ($R \sim 600$) of star-forming galaxies and AGNs show rich FSLs in mid-IR (10\,\mu m < \lambda_{\text{obs}} < 37\,\mu m).

By combining some FSLs and H recombination line (Humphreys $\alpha$), we can derive the elemental relative abundance ratios of Ne/H, S/H, etc... (but only for very nearby galaxies due to the limited sensitivity of Spitzer).
FSLs observed with Spitzer: metallicity

FSL-based Ne/S abundance ratio is significantly higher than the solar ratio. Probably, a part of S is depleted onto dust grains (while Ne is never depleted onto dust since Ne is a noble element).

FSL-based Ne/H abundance ratio is higher than optical-based Ne/H abundance ratio, possibly due to a higher gas metallicity at obscured parts in galaxies.
FSLs observed with Spitzer: gas density ($n_e$)

[SIII]18.71/33.48 flux ratio of nearby SINGS SF galaxies + AGNs
\[ n_e \sim 200-500 \text{ cm}^{-3} \]

This density is much higher than optical [SII]-based gas density of nearby galaxies ($n_e < 100 \text{ cm}^{-3}$).

ISM properties of gas in dust-obscured parts may be systematically different from those at un-obscured parts in galaxies?

Dale et al. (2008)
FSLs observed with Spitzer: ionization

Different ionization sources result in different ionization status of gas. FSLs in mid-IR can diagnose the ionization status of gas clouds even in dusty galaxies and AGNs.

ISM ionization status depends on metallicity, suggesting that simple “strong-line methods” with insufficient calibrations may result in large systematic errors in metallicity.
FSLs observed with Herschel

ISO/LWS spectrum of M82 (Colbert+99)

There are some strong FSLs in far-IR spectra of galaxies, which are useful for diagnostics.

Especially emission-lines of nitrogen are powerful to study the metallicity, given its nature as a secondary element.
FSLs observed with Herschel: metallicity

Photoionization models show that far-infrared [OIII] and [NIII] lines are actually useful to measure the metallicity, for both star-forming galaxies and AGNs.

Note that those metallicity indicators depend also on the ISM properties such as the ionization parameter.

Nagao et al. (2011)
Pereira-Santaella et al. (2017)
Rigopoulou et al. (2018)
FSLs observed with Herschel: MZR of IR galaxies

Optical metallicity diagnostics have suggested very low metallicities for LIRGs and ULIRGs. On the contrary, FIR metallicity diagnostics for LIRGs show much higher metallicity than optical (but still slightly lower than the expectation from the galaxy MZR).

The large discrepancy in MZR and optical metallicity for LIRGs is probably attributed to the obscuration (we observed only the outer part of dusty galaxies), but there is a slight evolutionary trend? Or the effect of SFR?

see also Rigopoulou et al. (2018)
FSLs observed with Herschel: at high-z?

Stacked spectra ($N_{\text{obj}} \sim 10-30$) of SMGs at $z\sim1-3$ show only marginal detection of [NIII]57 and upper limit of [OIII]51.

→ Inferred typical metallicity of SMGs is $Z_{\text{SMG}} > Z_{\odot}$.

Much more sensitivity is needed to study the high-redshift metallicity evolution of dusty galaxies through FSLs...
At high-z? $\rightarrow$ ALMA [NII] & [CII]

ALMA easily detects FSLs (not only [CII]) even for a z$\sim$5 SMG. For this object, the inferred metallicity is $Z_{\text{SMG}} \sim Z_{\text{sun}}$.

Caveats: [NII] is from ionized regions while [CII] from PDRs, so we may worry about possible systematic errors in models... and also dependences on ISM properties are concerns...
At high-z? → ALMA multi-line analysis

Another luminous SMG “COSMOS-AzTEC-1” at z=4.34

### Table 1
Summary of Observations and Line Properties in AzTEC-1

<table>
<thead>
<tr>
<th></th>
<th>ALMA Band-3</th>
<th>ALMA Band-6</th>
<th>ALMA Band-7</th>
<th>ALMA Band-9</th>
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<tr>
<td></td>
<td>CO (4–3)</td>
<td>[N II] 205μm</td>
<td>[C II] 158μm</td>
<td>[O III] 88μm</td>
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<td>2017/12</td>
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<td>14–1277</td>
<td>18–2967</td>
<td>32–2017</td>
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<td>frequency coverage</td>
<td>85.4–89.1</td>
<td>256.0–259.8</td>
<td>342.8–346.7</td>
<td>630.5–638.0</td>
</tr>
<tr>
<td>on-source time</td>
<td>420</td>
<td>300</td>
<td>32</td>
<td>100</td>
</tr>
</tbody>
</table>
At high-z? $\rightarrow$ ALMA multi-line analysis (contd.)

Cloudy model with HII+PDR: Estimating HII parameters from the inferred PDR parameters

Multi-FSL detection allows a modeling with HII region + PDR (with some assumptions such as the pressure balance, etc...).

Also for this high-z SMG, a moderately high metallicity is inferred ($Z_{\text{SMG}} \sim Z_{\odot}$), suggesting early chemical enrichment of SMGs (but with only low statistics).
At high-z? → ALMA [N\textsc{ii}] gas density

![Graph showing [N\textsc{ii}]122/[N\textsc{ii}]205 ratio vs. electron density.]

Comparison sample: local galaxies & AGNs observed with Herschel

- BR1202, a pair of SMG/QSO at z≈4.7

[N\textsc{ii}]122/[N\textsc{ii}]205 → electron density in H\textsc{ii} regions.

This flux ratio in BR1202 at z≈4.7 (a pair of SMG + QSO):
- SMG: comparable to local spirals measured with Herschel
- QSO: a slightly higher (but not extreme) density, log \( n_e \sim 2.1 \)

No significant difference between low-z and high-z?
→ Need statistics (but ALMA observations are expensive...)

Lee, Nagao, et al., submitted
Summary of previous missions

- **Spitzer**
  - enabled us to study detailed IR spectra (but only MIR)
  - metallicity studies with FSL & H lines (nearby objects)

- **Herschel**
  - far-IR spectra → various “strong-line methods”
  - (U)LIRGs do not show extreme deviation from MZR
  - still mostly for low-z galaxies, limited number of lines

- **ALMA**
  - far-IR spectra at very high-z (but only rest-frame FIR)
  - moderately-high ($\sim Z_{\text{sun}}$) metallicity in high-z SMGs
  - very expensive; hard to observe many objects/lines

Need to observe both MIR and FIR spectra for a large number of objects with more lines at wide redshift range
Expectations, or "the promise of SPICA"

Specifically for studies of chemical evolution of galaxies,

**Promise 1:**
Wide (and simultaneous) spectral coverage with extreme sensitivity in IR

**Promise 2:**
A systematic spectroscopic survey for galaxies/AGNs in a wide redshift range

A later talk by Fernandez Ontiveros (on Thursday) will tell us more specific strategy how SPICA will study the chemical properties of high-z galaxies/AGNs.

Spectroscopic survey → see Spinoglio’s poster