Mm/submm energy diagnostics in the ALMA era

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Astrochemistry as a tool for Astrophysics

• Feedback $\Rightarrow$ Astrophysical processes

$\Leftrightarrow$ Astrochemistry

• Different physical/heating processes (AGN, starburst) will produce different signature on the ISM

• PDR, XDR, MDR…
  $\rightarrow$ Chemical feedback

• Application: mm/submm spectroscopy can be a powerful tool to identify a dust-obscured energy source
Circumnuclear Disk (CND)

NGC 1097 HCN(4-3)

Izumi et al. 2013, PASJ, 65, 100

100 pc

NGC 7469 HCN(4-3)


330 pc

NGC 1068 CO(3-2)


NGC 1566 HCO+(1-0)


NGC 6951 HCN(1-0)


NGC 3227 HCN(1-0)


Typical spatial scale: ~100 pc
Molecular Energy Diagnostics
- to find elusive AGNs -

Submm HCN-diagram: ALMA Band 7 lines

[CI](1-0)/CO(1-0) diagnostic: new method under initial investigation
→ I will show new ALMA data obtained recently
1. Submm-HCN Diagram: Toward the submm-version of the BPT-diagram?

HCN-enhancement discriminates AGN and SB

AGN-dominated

SB-dominated

Non-LTE radiative transfer modeling of emission lines

- HCN(4-3)/HCO+ (4-3) 
  ※ T_b unit
- n_H2 = 10^5 cm^{-3}; T_{kin} = 50K, 100K, 200K
- **Filled** symbols
  → X(HCN)/X(HCO^+) = 10
- **Open** symbols
  → X(HCN)/X(HCO^+) = 1
- The abundance of HCN is enhanced in AGNs w.r.t. SB galaxies

High Gas Temperature Chemistry

- Neutral-neutral reactions are enhanced at $T > 300K$
- Efficient formation of HCN (e.g., CN + H$_2$ $\rightarrow$ HCN + H)
- Efficient destruction of HCO$^+$ (e.g., HCO$^+$ + H$_2$O $\rightarrow$ H$_3$O$^+$ + CO)

Origin of the high temperature?

Figure 1. Submillimeter-HCN diagram using HCN \((4-3)/\text{HCO}^+\)(4-3) and HCN \((4-3)/\text{CS}(7-6)\) integrated intensity ratios in the brightness temperature scale. Only the data obtained with high-resolution observations (spatial resolution < 500 pc, except for NGC 4945) are used. The red circles and the blue squares indicate AGNs and SB galaxies, respectively. The abbreviated names of AGNs are shown. Here the term "AGN" simply means that the galaxy hosts an AGN, regardless of its dominance in the total energy budget of the galaxy. See Table 1 for the details of the data. The systematic errors are also included here.

Figure 2. Same as Figure 1, but the whole sample, including both the high-resolution (spatial resolution < 500 pc; filled symbols) and the low-resolution (spatial resolution > 500 pc; open symbols) data, is plotted. The red circles, green diamonds, and blue squares indicate AGNs, buried AGNs, and SB galaxies, respectively (see also Table 1). The abbreviated names of AGNs and buried AGNs are shown. See Table 1 for the details of the data. The systematic errors are included here.

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\(L_X \approx 8 \times 10^{40} \text{erg/s}\)

\(L_X \approx 2 \times 10^{43} \text{erg/s}\)

Jet/mol. outflow

Time dependence of HCN abundance?


• We might select AGNs recently caused “mechanical feedback” by jet/outflow.
  → We can explain the time-dependent chemistry as well, since shocks reset the chemistry.
Brief Summary 1

- **AGN vs SB diagnostics** by using enhanced HCN intensity (w.r.t HCO$^+$ and CS) in AGNs (@ALMA Band 7)

- **Abundance variation of HCN** is responsible for the enhancement

- High-temperature neutral-neutral reactions can be natural explanation - maybe, this method is sensitive to AGNs recently caused mechanical feedback (jet/outflow)
2. A new method in the ALMA era

- $^{12}$CO ratio -

\[ C_{1s^22s^22p^2} \]

Too high energy

\[ ^1S \]
\[ ^1D \]

\[ ^3P \]
\[ ^3P_1 \]
\[ ^3P_0 \]

\[ ^3P_2 \]

\[ ^3P_2-^3P_1 \]
\[ (2-1) \]
\[ ^3P_1-^3P_0 \]
\[ (1-0) \]

<table>
<thead>
<tr>
<th>[Cl]</th>
<th>$\nu_{\text{rest}}$ [GHz]</th>
<th>$n_{\text{cr}@50K}$ [cm$^{-3}$]</th>
<th>$E_u$ [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3P_2-^3P_1$ (2-1)</td>
<td>809.34</td>
<td>3000</td>
<td>62.5</td>
</tr>
<tr>
<td>$^3P_1-^3P_0$ (1-0)</td>
<td>492.16</td>
<td>500</td>
<td>23.6</td>
</tr>
</tbody>
</table>

Too high energy
Idea: X-ray dissociation: $\text{CO} \rightarrow \text{C}^0$

- We can easily expect much more efficient CO dissociation in XDRs than in PDRs. $\rightarrow$ Efficient formation of $\text{C}^0$

- Underlying physics/chemistry is rather simple!
Why submm people like [Cl] line(s)?

- Easy to solve line excitation → There are only two transitions
- Good tracer of molecular mass!!
- We can observe them in high-z objects (z ~ 5)

Glover et al. (2015)
Current status of [CI] observation

• There is only ONE spatially resolved extragalactic [CI](1-0) measurement → NGC 253 (Krips et al. 2016)
• This indicates that [CI] line is really a new tool for extragalactic (but rather nearby) studies.
• [CI](1-0)/CO(1-0) ratio ~ 0.4 at the center (T_B unit)

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[Image: Color map of [CI](1-0)/^{12}CO(1-0) ratio with contours for NGC 253 (SB galaxy).]

Krips et al. (2016)
Our ALMA Cycle 4 Study: Circinus galaxy (AGN)

- The nearest (4.2 Mpc) type-2 Seyfert → high spatial resolution (~20 pc/arcsec)

- $L_{2-10\text{keV}} = 4 \times 10^{42}$ erg/s (Marinucci et al. 2012) → Strong XDR may extend to ~20-30 pc (Schleigher et al. 2010)

- Our objective: compare $\text{[Cl]}(1-0)/\text{CO}(1-0)$ ratio with NGC 253 (Starburst)

<table>
<thead>
<tr>
<th>Line</th>
<th>Band</th>
<th>$\theta$ (pc x pc)</th>
<th>$1\sigma$ (mJy/beam)</th>
<th>dV (km/s)</th>
<th>$t_{\text{on-source}}$ (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{[Cl]}(1-0)$</td>
<td>8</td>
<td>13 x 12</td>
<td>7.5</td>
<td>2.8</td>
<td>1.2</td>
</tr>
<tr>
<td>$\text{CO}(3-2)$</td>
<td>7</td>
<td>5.7 x 4.5</td>
<td>1.8</td>
<td>3.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

→ I need to convert $\text{CO}(3-2)$ flux to $\text{CO}(1-0)$ flux
Now you can see that [CI](1-0) is clearly concentrated toward the AGN position! → indicate the CO dissociation

Then, measure [CI](1-0)/CO(1-0) ratio next → compare with NGC 253 - (3-2)/(1-0) flux ratio ~ 25 @NGC 1068 (Viti et al. 2014) is assumed
The ratio is 5x higher in Circinus (AGN) than in NGC 253 (Starburst). → support our claim that the ratio is enhanced in AGNs!

We plan to expand the sample number to confirm this trend.
• [CI](1-0)/CO(1-0) (or other transitions?) can be a new identifier of AGNs → Efficient CO dissociation to C⁰ in XDRs

• We indeed found x5 enhanced ratio in Circinus (AGN) than in NGC 253 (SB): these are only two galaxies with spatially resolved [CI](1-0) measurements at this moment…

• We plan to expand the sample from next ALMA (cycle 6~?)
Summary

• **AGN vs SB diagnostics** by using enhanced HCN intensity (w.r.t HCO\(^+\) and CS) in AGNs (@ALMA Band 7)

• **Abundance variation of HCN** is responsible for the enhancement

• High-temperature neutral-neutral reactions can be natural explanation - maybe, this method is sensitive to AGNs recently caused mechanical feedback (jet/outflow)

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Backup
PDR and XDR

- Basically a simple layered structure driven by UV photons
- But in actual, interstellar turbulence mixes layers (e.g., Offner et al. 2014)
PDR and XDR

- Extends over a large volume → No layered structure
- Driven by X-ray photons (and yielded e.g., electrons)
- Much more efficient heating than in PDRs

Maloney et al. (1996)
Submm HCN-diagram:
Case study in NGC 1097

- $\text{HCN}(4-3)/\text{HCO}^+(4-3) > 1$
- $\text{HCN}(4-3)/\text{CS}(7-6) > 10$
- Similarly high ratios in another AGN (NGC 1068)
- These high ratios are not seen in Starburst galaxies

→ Watching the Feedback from AGNs? Key feature to identify AGNs?

Izumi et al. 2013, PASJ, 65, 100
Non-LTE modeling of line radiative transfer

- We use a RADEX code
  - http://home.strw.leidenuniv.nl/~moldata/radex.html

- Statistical equilibrium:
  - Collisional process
  - Radiative process
  - Background radiation

- Optical depth is treated with an escape probability method

- Input parameters:
  \( n_{\text{H}_2}, T_{\text{kin}}, T_{\text{bg}}, dV, N_{\text{mol}} \)

- We assume a spherical, uniform, single cloud for the modeling