A Chandra and ALMA Study of X-ray-irradiated Gas in the Central ~100 pc of the Circinus Galaxy

(Kawamuro et al. 2019a)

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(red = [S II], green = Hα+[N II], blue = [O III]; Maiolino+94)
Co-evolution; AGN and SF relation

- Understanding of the co-evolution b/w SMBHs and galaxies.
  → Relation b/w AGN and SF activities.

- Outflows by AGN.
- X-ray irradiation by AGN.
  → This is an un-avoidable AGN effect on the host galaxy.
Extended X-ray emission

- Chandra has revealed detailed spatial structures. (e.g., Tsunemi+01; Mori+01; Li+03,04)
- Growing number of reports of extended X-ray emission (e.g., Wang+09; Marinucci+13,17; Feruglio+19)

![Extended X-ray emission diagram]
### X-ray Irradiation of the ISM

- X-ray irradiation causes a change of the chemical composition. → **X-ray Dominated Region (XDR)**
- In the vicinity of an X-ray src, molecular dissociation is expected.

\[ \xi_{\text{eff}} = \frac{L_X}{R^2 n_{H_2} N^{1.1}_{\text{att}}} \]

(Maloney+96)

**Diagram:**
- **X-ray**
- **Highly Ionized Region**
  - High \( H_X/n \)
  - Low \( H_X/n \)
- **Chemical Composition**:
  - \( H \): \( H/H_2 \sim 0.01 \)
  - \( H_2 \)
  - \( T \sim 10^4 K \)
  - \( T \sim 2000 K \)
  - \( T < 200 K \)
  - \( C^+, C \)
  - \( C, C^+ \)
  - \( CO, C, C^+ \)
  - \( O \)
  - \( O \)
  - \( O, OH, O_2, H_2O \)
  - \( Fe^+ \)
  - \( Fe^+ \)
  - \( Fe^+, Fe \)
  - \( X_e \sim 10^{-1}-10^{-2} \)
  - \( X_e \sim 10^{-3}-10^{-2} \)
  - \( X_e < 10^{-3} \)
SF and Phases of Gas

- Why do we care about the mol. gas dissociation?

- The positive correlation b/w $\Sigma_{\text{mol}}$ and $\Sigma_{\text{SFR}}$ suggests a causal link b/w mol gas and the ability to form stars.

- A naive expectation is that X-ray emission can suppress SF by dissociating molecules.
Target: the Circinus galaxy

- $D = 4.2$ Mpc ($1'' \sim 20$ pc).
- A Compton-thick AGN host.
  → Good for detecting faint, extended emission.

Obs.: Chandra & ALMA

- high spatial res. ($< 1''$).
- high penetrating power of X-ray & submm/mm.
  → Good to study the dense nuclear region with the least bias.
- high S/N data.
Fluorescent Iron-Kα Line as a Probe

- The iron-Kα line probes X-ray irradiation regions.
- $6.2-6.5$ keV/3.0-6.0 keV ratios → an proxy of the EW (Fe-Kα)
- $\tau \sim 1$ for the X-ray w/ the edge energy when $\log N_H/cm^{-2} \sim 23.9$
X-ray irradiation

- Multiple regions w/ bright Ka emission
- High EWs (> 1 keV) are consistent w/ being irradiated by an X-ray src.
Spatial anti-correlation b/w mol. and iron lines

- **HCO+(4-3)**
  - Molecular gas
  - high critical dens.
    - dense gas tracer
- **Iron-Kα line**
  - gas irrespective of atomic/mol. phases

![Image of spatial correlation map]

HCO+(4-3)

6.2-6.5 keV/3.0-6.0 keV
(X-ray nuc. emission subtracted)

Declination

Right ascension

-65°20'15.0"
### Spatial anti-correlation b/w mol. and iron lines

- **HCO+(4-3)**
  - Molecular gas
  - high critical dens.
    - = dense gas tracer
- **Iron-Kα line**
  - gas irrespective of atomic/mol. phases
- **Clear atomic-to-mol. transition boundaries**
- **Mol. dissociation?**
- **Next is quantitative discussion w/ XDR model**

$$\xi_{\text{eff}} = \frac{L_X}{R^2 n_{\text{H}_2} N^{1.1}}$$
Physical state of the ISM

- Multiple mol. line detections by ALMA

- Line ratios are compared w/ statistical equilibrium calculations involving collisional and radiative processes. (i.e., non-LTE code by van der Tak+07)

→ constrains on $N_{\text{H}_2}$, $n(\text{H}_2)$, $T_k$, $[\text{HCN}]/[\text{HCO}^+]$

<table>
<thead>
<tr>
<th></th>
<th>Nucleus</th>
<th>CNR-SE</th>
<th>CNR-E</th>
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</thead>
<tbody>
<tr>
<td>log $N_{\text{H}_2}$ [cm$^{-2}$]</td>
<td>24.5 [25.0]</td>
<td>23.5 [24.5-25.0]</td>
<td>24.5 [20.0-25.0]</td>
</tr>
<tr>
<td>log $n_{\text{H}_2}$ [cm$^{-3}$]</td>
<td>5.0 [4.5]</td>
<td>4.5 [3.0-4.0]</td>
<td>3.5 [3.0-5.0]</td>
</tr>
<tr>
<td>$[\text{HCN}]/[\text{HCO}^+]$</td>
<td>3 [-]</td>
<td>4 [2-5]</td>
<td>2 [3-4]</td>
</tr>
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</table>
Is the X-ray powerful enough?

\[ \xi_{\text{eff}} = \frac{L_X}{R^2 n_{H_2}} N_{\alpha \text{att}} \]

\[ L_X \sim 1.3 \times 10^{43} \text{ (1–100 keV)} \]

(NuSTAR estimate by Arevalo+14)

\[ R \sim 60 \text{ pc} \]

(spatially resolved map)

\[ n_{H_2} \sim 1 \times 10^{3.0-5.0} \text{ cm}^{-3} \]

(mol. line ratios fit by RADEX)

\[ N_{\alpha \text{att}} \sim 1 \times 10^{23.9} \text{ cm}^{-2} \]

(\( \tau \approx 1 \) for the neutral iron)

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</thead>
<tbody>
<tr>
<td>log ( \xi_{\text{eff}} )</td>
<td>&lt; -4.0</td>
<td>-4.6~2.6</td>
<td>-4.0~2.5</td>
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SF in the X-ray irradiated region

- PAH emission study using Gemini-S/T-TeCS by Roche+06.
- Less extinct PAH emission in E → SF in the foreground of the dust lanes
  → in-active SF in X-ray irradiate region
Summary

- AGN usually emit X-rays, and therefore the X-ray irradiation is an un-avoidable effect on the host galaxy.

- Chandra and ALMA obs. have revealed the spatial anti-correlation b/w the molecular gas and iron-Kα line emission.

- Moderately high ionization parameters are consistent with molecules being dissociated by the X-ray emission.

- The high-spatial resolution study is important.
  → We anticipate the future high spatial-resolution projects, such as MIXIM, AXIS, Lynx.