MOLECULES IN THE CIRCUMNUCLEAR DISK OF THE GALACTIC CENTER

Implications from Chemical Modeling

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Molecular View of Circumnuclear Disk

- Circumnuclear disk/ring is a molecular ring composed of clumpy molecular clouds.
- Distance: ~ 2-7 pc away from Sgr A* 
- Uncertainty in the density of molecular clouds ($n=3 \times 10^4\text{--}10^7\text{cm}^{-3}$) (e.g., Requena-Torres et al. 2012, Christopher et al. 2005)
- T~200 & 500 K component (Requena-Torres et al. 2012)

➡ Next talk by M. Requena-Torres
Line survey in the southwest lobe of CND

* A part of large line surveys of multiple positions in the Galactic Center which covers most of 80 - 500 GHz frequency range. →Poster by D. Riquelme (P13).

* IRAM 30 m telescope data in 3mm & 2mm bands

* APEX telescope FLASH 345 & 460 (MPIfR PI receiver)

Wide IF Bandwidth of 4x4 GHz
Perfect for efficient line surveys!
The survey covers higher excitation lines such as HCN J=5-4, CS J=9-8, HCO⁺ J=4-3
Analysis

- Large velocity gradient (LVG) analysis
- Radex (van der Tak et al. 2007) based code written by D. Riquelme
- A component around -80 km/s is used.
- A source size of 0.3 pc is assumed.
- A parameter range of $n = 10^2$-$10^7$ cm$^{-3}$, $N=10^{12}$-$10^{19}$ cm$^{-2}$, $T_{\text{kin}}=100$, 300, and 500 K is used.

- Best-fit densities are $10^5 \leq n < 10^6$ cm$^{-3}$

⇒ The density is less than the Roche limit $8 \times 10^7$ cm$^{-3}$, and the cloud is gravitationally unstable.
**Column Densities**

- Column densities for 12 species obtained from LVG analysis.
- C$_2$H and CH$_3$OH were detected, but lines are blended, and unable to separate different velocity components.
- CO column densities from Requena-Torres et al. (2012)

<table>
<thead>
<tr>
<th>X</th>
<th>$N_X$ (cm$^{-2}$)</th>
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<tr>
<td>CO</td>
<td>$3.00 \times 10^{18}$</td>
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<tr>
<td>HCN</td>
<td>$1.20 \times 10^{16}$</td>
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<td>H$_3$O$^+$</td>
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<td>H$_2$CO</td>
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<tr>
<td>HC$_3$N</td>
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</tr>
<tr>
<td>SiO</td>
<td>$6.20 \times 10^{13}$</td>
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<tr>
<td>CO</td>
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<td>HCN</td>
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<td>SiO</td>
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</tbody>
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Physical Conditions that Affect Chemistry

- Cosmic-ray ionization rate
- Tracer of lower energy cosmic-rays
- Galactic dense clouds $\zeta \sim 10^{-17}$ s$^{-1}$, diffuse ($n \sim 100$ cm$^{-3}$) clouds $\zeta \sim 10^{-16}$ s$^{-1}$
- Enhancement in CMZ in diffuse clouds ($\zeta = 10^{-15}$ s$^{-1}$ or higher, Goto 2008; $\zeta = 10^{-15} - 10^{-14}$ s$^{-1}$ Yusef-Zadeh et al. 2013)
- They affect chemistry by ionization and dissociation of molecules from internally generated UV-photons
- Constant injection of cosmic-ray of lower energy ($E < 10$ GeV) cosmic-rays for $10^4$ yrs reproduces observed spectra of gamma rays (models by Chernyakona et al. 2011)
Physical Conditions that Affect Chemistry

* X-ray ionization
* Similar effect on chemistry as cosmic-rays
* They penetrate $N \sim 10^{24} \text{cm}^{-2}$
* $L_X \sim 2 \times 10^{33} \text{ergs}^{-1}$ in 2-10 keV range with a photon index of $\Gamma = 2.7$ in a quiescent phase (Baganoff et al. 2003).
* A current X-ray flux is too weak to affect the chemistry compared with cosmic-ray ionization rate.
* Higher X-ray activities in the past may affect the chemistry if they were long term.

\[ \zeta = 10^{-17} \text{s}^{-1} \]

\( \text{distance (pc)} \)

\( n = 10^5 \text{cm}^{-3} \)

\( \text{with Current Flux} \)

\( \text{with } x1000 \text{ Enhanced Flux} \)
Physical Conditions that Affect Chemistry

- UV-photons from star cluster
  
  There is a star cluster in the central parsec providing ionizing photons of $2 \times 10^{50} \text{s}^{-1}$, $T_{\text{eff}} \leq 35,000 \text{ K}$ (Lacy et al. 1980)

- UV-radiation field can be estimated to be roughly $G_0 \sim 10^4 - 10^5$

- UV-photons ionize and dissociate molecules.

- They penetrate until $A_v \sim 5 \Rightarrow N = 10^{22} \text{cm}^{-2} \rightarrow$ when $n = 10^5 \text{cm}^{-3}$, and source size of 0.3pc is assumed, $\sim 10\%$ is photon-dominated regions (PDRs).

- Shock waves
  
  Shock waves provide efficient heating, and it is a likely source of heating in CND (Bradford et al. 2005, Requena-Torres et al. 2012) and other Galactic Center molecular clouds (Ao et al. 2012).

- Shock waves also sputter grain ices & mantles, which is proposed as an explanation of abundant SiO (Schilke et al. 1997)
Chemical Models

- Models of the evolution of molecular abundances


- The reaction network contains ~200 species, ~2400 reactions

- Phase I: collapse (diffuse to dense cloud)

- Phase II: shock passage & enhancement of cosmic-rays
Chemical Models

- Parameters
  - Cosmic-ray ionization rate: $\zeta=10^{-17} - 10^{-14}\text{s}^{-1}$
  - Pre-shock densities: $n=10^4$, $10^5$, $10^6\text{ cm}^{-3}$
  - Shock velocities: $v=10$, 20, 30, 40 km s$^{-1}$
    \[ T_{\text{max}} = 400, 1000, 2000, 3000\ \text{K} \]
    respectively
  - Elemental abundances
    - There are large uncertainties for the degree of depletion onto grains in metals - S, Mg, Si, etc.
    - Effects of UV-photons are modeled separately with Meudon PDR code (Le Petit et al. 2006).

<table>
<thead>
<tr>
<th>Element</th>
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<th>E2</th>
<th>E3</th>
<th>E4</th>
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<tbody>
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<td>2.4e-6</td>
</tr>
</tbody>
</table>

- “Low-metal” abundances
- Solar abundances
Overall fit to the observation

- Goodness of fit $\kappa = \langle \kappa_i \rangle$ (Garrod et al. 2007).

$$\kappa_i = \text{erfc} \left( \frac{|\log(X_i) - \log(X_{\text{obs},i})|}{\sqrt{2}\sigma} \right)$$

$\kappa=1 \Rightarrow$ perfect match

- Higher the cosmic-ray ionization rate is, the better the agreement is up to $10^{-14}\text{s}^{-1}$. 
Molecular Abundances

* "Best-fit" model for n=10^5 cm^-3

* $\zeta = 10^{-14} s^{-1}$

* Most species agrees within a factor of a few at the time of best agreement $t \sim 10^4$ yrs.

* Discrepancy: underabundant CN and CS, overabundant HNC

* CN: Its abundance can increase in PDRs.

* CS: sulfur abundances may increase in PDRs.

* HNC: It can decrease by a reaction $H + HNC \rightarrow HCN + H$ in high temperature.
Is the cosmic-ray ionization rate actually high?

- What is the discrepancy if zeta is lower?
- When $\zeta=10^{-15}\text{s}^{-1}$, CN, HCO$^+$ is more underabundant.
- CN, HCO$^+$ can be enhanced in PDRs.
- When $\zeta=10^{-16}\text{s}^{-1}$, CN, HCO$^+$ is even more underabundant. In early time, NO, HC$_3$N, SiO is underabundant. In late time, H$_2$CO, N$_2$H$^+$ is underabundant.
Limitation:
Observation & Models

- Many components are likely to be included in the beam.
- Density components may vary from $10^4 \text{cm}^{-3}$ to $10^7 \text{cm}^{-3}$.
- Diffuse components are affected more by UV-photons due to less shielding column densities, and cosmic-rays due to higher $\zeta/n$.
- There are many more model parameters that need to be considered than that are used here.
- Number of shock waves and their timelines.
- Time of cosmic-ray turn-on.
Summary

Chemical models with higher cosmic-ray ionization rate of $\zeta = 10^{-14}$ s$^{-1}$ matches the observation in the molecular cloud of the southwest lobe of CND best.

Lower ($\zeta \sim 10^{-15}$ s$^{-1}$) cosmic-ray ionization rate can also be fit to the observed abundances with an effect of UV-photons.

Future work

Higher spatial resolution map of selected species helps identify the emission from a single component.

ALMA

More complex physical conditions need to be considered in the chemical models.

More chemical reactions especially more detailed treatment of surface reactions (e.g. Garrod et al. 2008) need to be included.