DNC/HNC Ratio in Molecular Clumps

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Cluster formation

- Most of stars (~90%) are born in clusters (Lada & Lada 2003).

- How do clumps fragment into small cores?
- How and when is the mass of each cluster member determined?
- How does star formation activity affect fragmentation?
- Is there diversity of cluster formation mechanism?
Deuterium Fractionation

• Molecules are highly deuterated in molecular clouds.

\[
\begin{align*}
H_3^+ + HD & \rightarrow H_2D^+ + H_2 + 230 \text{ K} \\
CH_3^+ + HD & \rightarrow CH_2D^+ + H_2 + 370 \text{ K} \\
C_2H_2^+ + HD & \rightarrow C_2HD^+ + H_2 + 550 \text{ K}
\end{align*}
\]

• CO depletion (< ~20 K).

\[
H_2D^+ + CO \rightarrow HCO^+ + HD
\]
Deuterium Fractionation
$
\frac{\text{H}_2\text{D}^+}{\text{H}_3^+}
$

- **Diffuse cloud**
- **Starless Core**
- **CO Depletion**
- **CO Sublimation**

Chemical reactions:

- $\text{H}_3^+ + \text{HD} \rightarrow \text{H}_2\text{D}^+ + \text{H}_2$
- $\text{H}_2\text{D}^+ + \text{CO} \rightarrow \text{HD} + \text{HCO}^+$

**Time**
Deuterium Fractionation
\( \text{N}_2\text{D}^+/\text{N}_2\text{H}^+ \), as well as \( \text{H}_2\text{D}^+/\text{H}_3^+ \), is sensitive to the “current” temperature.
Deuterium Fractionation
DNC/HNC

DNC/HNC ratio of star-forming regions may have information of their cold starless phase.

DNC + HCO⁺ → DNCH⁺ + CO
N₂D⁺/N₂H⁺
N₂D⁺ + CO → N₂ + DCO⁺

DNC/HNC ratio does not rapidly decrease after the onset of star formation.
Single-dish Survey of DNC/HNC toward Molecular Clumps

• Nobeyama 45 m
  – DNC $J=1-0$ (76 GHz)
  – HN$^{13}$C $J=1-0$ (87 GHz)
    • Beam size ~20"

• Targets
  – IRDCs: starless (24 µm dark) & star-forming (24 µm source)
    • Rathborne et al. 2006; Sridharan et al. 2005; Beuther et al. 2002
  – HMPOs
    • Sridharan et al. 2002; Beuther et al. 2002
Survey of DNC/HNC with NRO 45 m


- IRDCs < HMPO
The third most massive clump in G34.43+00.24 (Rathborne et al. 2006)

Distance
- 1.56 kpc (VLBI: Kurayama et al. 2011)
- 3-4 kpc (kinetic distance or extinction; Foster et al. 2012)

Mass
- \( \sim 30 M_{\text{sun}} \) (D=1.56 kpc)
- \( \sim 171 M_{\text{sun}} \) (D=3.7 kpc)
  - Rathborne et al. 2010

ALMA cycle 0
- Band 6 and Band 7
- Antenna
  - 23-26
- Beam size: \( \sim 0.8'' \)
• The DNC emission is more extended than the HN$^{13}$C emission.
Results

DNC, HN\textsuperscript{13}C and CH\textsubscript{3}OH

- HN\textsuperscript{13}C -> Hot core
- DNC -> Extended around the hot core

$E_u = 165$ K
Results

DNC, HN$^{13}$C, CH$_3$OH and CS

- The DNC peaks are offset from the CS peaks.
  - Shock chemistry does not affect to the formation of DNC.
Results

\textbf{DNC}, \textbf{HN}^{13}\textbf{C}, \textbf{CH}_3\textbf{OH}, \textbf{CS} and \textbf{N}_2\textbf{H}^+

- No \textbf{N}_2\textbf{H}^+ emission near the hot core.
  - \textbf{N}_2\textbf{H}^+ + \textbf{CO} \rightarrow \textbf{HCO}^+ + \textbf{H}_2
• No $N_2H^+$ emission near the hot core.
  
  - $N_2H^+ + CO \rightarrow HCO^+$

  DNC emission can trace warm (>20 K) regions.
Difference between single-dish and ALMA observations

- The DNC emission is stronger than the HN$^{13}$C emission.
  - Apparently inconsistent with the single-dish results.

(a) NRO 45 m
DNC/HNC $\sim 0.003$

(b) ALMA (Average) $15'' \times 15''$
DNC/HNC $>0.06$
Difference in Critical Density

- **NRO 45 m**
  - DNC & HN^{13}C
    - $J=1-0$
      - $n_{cr} \sim 10^5$ cm$^{-3}$
  - ALMA
    - DNC & HN^{13}C
      - $J=3-2$
      - $n_{cr} \sim 10^7$ cm$^{-3}$

Model Calculation Results

- **Observation (ALMA)**
  - $10^6$ cm$^{-3}$
- **Observation (NRO 45 m)**
  - $10^4$ cm$^{-3}$
Summary: DNC/HNC in G34.43+00.24 MM3

High Density Regions ($\sim 10^6 - 7$ cm$^{-3}$)
DNC/HNC ($>0.03$)

Hot Core
DNC/HNC (0.001–0.004)
Low DNC/HNC ratio in Ice mantle

Low Density Envelope ($\sim 10^{4.5}$ cm$^{-3}$)
DNC/HNC ($\sim 0.003$)
Summary: DNC/HNC in G34.43+00.24 MM3

- High Density Regions (~$10^{6-7}$ cm$^{-3}$)
  - DNC/HNC (>0.03)

- Hot Core
  - DNC/HNC (0.001-0.004)
  - Low DNC/HNC ratio in Ice mantle

- Low Density Envelope (~$10^{4-5}$ cm$^{-3}$)
  - DNC/HNC (~0.003)
Origin of Diversity of DNC/HNC

Filling factor of dense regions
Origin of Diversity of DNC/HNC

- In any cases, different DNC/HNC ratio suggests different history of the cluster formation.

Timescale of cold phase

High resolution observations are necessary => ALMA Cycle 3
Summary

• DNC/HNC
  – can be high in warm regions.
  – depends on density.
    • Multi-transition line observations
      -> ALMA Band 2 (70 GHz-band)

• Diversity of DNC/HNC
  – Diversity of cluster formation?

High resolution observations are crucial.

Summary: DNC/HNC in G34.43+00.24 MM3

High Density Regions (~$10^6-7$ cm$^{-3}$)
DNC/HNC (>0.03)

Hot Core
DNC/HNC (0.001-0.004)

10$^6$ cm$^{-3}$
10 K

[Graph showing DNC/HNC over time with two regions highlighted: gas and ice]
DNC/HNC toward the Hot Core

- **HN$_{13}$C**
  - Hot core (> 90 K)
- **DNC**
  - Offset from the hot core
Chemical Model Calculations

(a) Constant temperature of 10 K
(b) Temperature-rise at 3x10^4 yr

Abundance vs. Time [yr]

Abundance vs. Time after temperature-rise [yr]
Chemical Model Calculations

- Temperature rises from 10 K to a given temperature at a given time.
o/p ratio
Interaction between the Outflow and Ambient Gas

- Channel maps of $\text{N}_2\text{H}^+ \ J=3-2$ and $\text{CS} \ J=5-4$
- The outflow is penetrating into cold gas
- The outflow should be very young.

- \( \text{CH}_3\text{OH} J_K=9_{-1}^{+8}_0 \): shock excited maser
Results: Keck

K-band (grey scale)

$\text{CH}_3\text{OH } J_K^{10,2-9,3} \ A^-$ (red contour)

$\text{CS } J=5-4$ (blue contour)

Right Ascension (J2000)

Declination (J2000)

1°28'88"

20"

3000 AU