Chemical Modeling of Starless Cores
--- L1512

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Lin et al. submitted
Outline

• Introduction: Starless cores and Formation
• Deuterium Chemistry
• Analysis
• Summary
Starless Core

- The earliest phase in star formation
- C-, S-bearing species are depleted
- N-bearing/Deuterated species are abundant
- High **Deuteration** fraction
  - \([D]/[H] \gg \text{Cosmic } [D]/[H] \approx 3.2 \times 10^{-5}\)
Starless Core Formation

**Question:** Do starless cores form via slow or fast process?

**Slow Dynamical Model**
- Ambipolar diffusion (e.g., Mouschovias 1991)
- Time scale: $\sim 10$ Myr if $n \sim 10^4$ cm$^{-3}$

**Fast Dynamical Model**
- Supersonic turbulent flows, Freefall (e.g., Klessen+2000)
- Time scale: $\sim 0.5$ Myr if $n \sim 10^4$ cm$^{-3}$

(Bergin+2006)
Starless Core Formation

Question: Do starless cores form via slow or fast process?

**Fast Dynamical Model**
- Supersonic turbulent flows, Freefall (e.g., Klessen+2000)
- Time scale: \( \sim 0.5 \text{ Myr if } n \sim 10^4 \text{ cm}^{-3} \)

**Slow Dynamical Model**
- Ambipolar diffusion
- Time scale: \( \sim 10 \text{ Myr if } n \sim 10^{4-5} \text{ cm}^{-3} \)

Chemical analysis provides another estimation on the lifetime scale.

(Bergin+2006)
Deuterium Chemistry

- Starless [D]/[H] >> Cosmic [D]/[H] ≈ 3.2 × 10⁻⁵
- Deuterium fractionation is enhanced in the cold environment
- Spin states matter! e.g., ΔE(o-H₂ - p-H₂) = 170 K

(Pagani+2009)
Solve the Time scale!

- 4 Key cation tracers: o-H$_2$D$^+$, N$_2$H$^+$, N$_2$D$^+$, DCO$^+$
- The freeze-out process is dominated
- CO and N$_2$ are depleted and their abundances are constant

(Pagani+2009)
Analysis

Abundance Profiles
($N_2H^+$, $N_2D^+$, DCO$^+$, o-$H_2D^+$)

Lifetime of L1512

Chemical Modeling with the Deuterium Network

CO & $N_2$ Profiles
Analysis

1D Spherical Non-LTE Radiative Transfer with an Onion-shell Model

- Multi-line Obs of the 4 tracers
- Density Profile
- $T_{\text{kin}}$ Profile
- Abundance Profiles ($N_2H^+, N_2D^+, DCO^+, o-H_2D^+$)

Lifetime of L1512

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Perform a Plummer-like density profile fitting on the extinction map

Azimuthal average

Density Profile

\[ n(r) = \frac{n_0}{1 + \left(\frac{r}{R_0}\right)\eta} \]

Av profile fitting

Av model map

N_{H_2}/A_v = 5.3 \times 10^{20} \text{ cm}^{-2} \text{ mag}^{-1}  
(Bohlin+1978)

N_{H_2} model map

Sphere (n_{H_2})
Analysis: Radiative Transfer

We used the radiative transfer tool originally written by Bernes (1979) and revised by Pagani+ (2007).
Analysis

Multi-line Obs of the 4 tracers

SCUBA2 850um map & Pointing positions
Profiles of L1512

\[ n_{\text{H}_2} \, [\text{cm}^{-3}] \]

\[ T_{\text{kin}} \, [\text{K}] \]

\[ V_{\text{turb}} \, [\text{m/s}] \]

\[ \frac{[\text{N}_2\text{D}^+]}{[\text{N}_2\text{H}^+]} \rightarrow \frac{[\text{DCO}^+]}{[\text{D}]}/[\text{H}] \]

Depletion factor

<table>
<thead>
<tr>
<th>L1512</th>
<th>L183</th>
<th>L1544</th>
</tr>
</thead>
<tbody>
<tr>
<td>[N\textsubscript{2}H\textsuperscript{+}] [10\textsuperscript{17}] to [10\textsuperscript{13}]</td>
<td>6 [10\textsuperscript{13}]</td>
<td>&gt;100</td>
</tr>
<tr>
<td>4 \textsuperscript{+} 2 \textsubscript{−1}</td>
<td>2 to 2.5</td>
<td>~15</td>
</tr>
<tr>
<td>9 \textsuperscript{+} 21 \textsubscript{−3}</td>
<td>&gt;17</td>
<td>~10?</td>
</tr>
<tr>
<td>~10</td>
<td>~2</td>
<td>---</td>
</tr>
</tbody>
</table>

This work: Pagani+ 2007, 2009, 2012

Redaelli+ 2019
IRAM30m $N_2H^+$ J,F=1,2-0,1 (central triplet)

IRAM30m DCO$^+$ 2-1

JCMT HARP $o-H_2D^+$ 1$_{10}$-1$_{11}$
Analysis: Chemical Model

- Pseudo time-dependent NAHOON code (Wakelam 2006) updated with our deuterium chemical network (Pagani+2009)
- The lower limit of the lifetime is $2.5\sim3.5$ Myr

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Abundance Profiles
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Lifetime of L1512
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Analysis: Chemical Model

- $^{12}$CO and $N_2$ abundance profiles

**Depletion factor**

$^{12}$CO: $\sim 430–870$

$N_2$: $\sim 300$

- Validate with the $^{18}$O data by assuming $[^{18}$O$]= [^{12}$CO$]/500$
Summary

1. We find $n_{H_2} = 1.1 \times 10^5$ cm$^{-3}$ and $T = 7.5 \pm 1$ K at the center. The depletion factors of $N_2H^+$ and $N_2D^+$ are $27^{+17}_{-13}$ and $4^{+2}_{-1}$ in L1512, intermediate between the two other more advanced and denser starless core cases, L183 and L1544.

2. We find that CO has a depletion factor of $\sim 430–870$ and the $N_2$ profile is similar to that of CO. Thus, L1512 has probably been living long enough so that $N_2$ chemistry has reached steady state.

3. $N_2H^+$ modeling remains compulsory to assess the precise physical conditions in the center of cold starless cores. L1512 is presumably older than 2.5–3.5 Myr, suggesting that the dominating core formation mechanism could be ambipolar diffusion.