Molecules in Diffuse ISM

Diffuse clouds are not chemical warehouses like dense clouds. Some diatomic molecules -- H$_2$, OH, NH, CH, CH$^+$, CN, CO, and C$_2$ -- have been observed in many diffuse clouds. The triatomic molecule C$_3$ was tentatively detected toward the “translucent” cloud HD 147889 (see below).

A much simpler chemistry is expected in diffuse clouds because they are not completely opaque to ultraviolet starlight. In dense clouds, nearly 100% of C is in the form of CO -- in diffuse clouds, this fraction is closer to 1%. At most about half of H is in the form of H$_2$.


**H$_3^+$ Chemistry**

**Formation Mechanism:**
The formation for H$_3^+$ in diffuse clouds is the same as for dense clouds.

**Step 1:** Cosmic-ray ionization of H$_2$:

$$\text{H}_2 \xrightarrow{\text{cosmic ray}} \text{H}_2^+ + e^-$$

Rate = $\zeta \cdot n(\text{H}_2)$

**Step 2:** Ion-Molecule reaction with H$_2$:

$$\text{H}_2 + \text{H}_2^+ \rightarrow \text{H}_3^+ + \text{H}$$

[occurs on every collision]

**Destruction Mechanism:**
Since molecules (e.g. CO) are less abundant than in dense cloud, the dominant destruction path of H$_3^+$ is electron recombination.

$$\text{H}_3^+ + e^- \rightarrow \text{H} + \text{H} + \text{H} \quad (75\%)$$

$$\rightarrow \text{H} + \text{H}_2 \quad (25\%)$$

Rate = $k_e \cdot n(\text{H}_3^+) \cdot n(e^-)$

$k_e \sim 2 \times 10^{-7}$ cm$^3$ s$^{-1}$
Steady State $n(H_3^+)$

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Assuming steady-state, the $H_3^+$ number density can be derived by equating the rates of formation and destruction.

Formation Rate (cosmic rays): $\zeta \ n(H_2)$

Destruction Rate (recombination): $k_e \ n(e^-) \ n(H_3^+)$

Let $n(H_2) \equiv (f/2) \cdot n(\Sigma H)$, where $f$ is the fraction of H in molecular form. Assume electrons come from ionization of C, and all C is ionized, so $n(e^-) = n(C^+) \sim n(\Sigma C)$.

$$n(H_3^+) = \frac{f\zeta}{2k_e} \cdot \frac{n(\Sigma H)}{n(\Sigma C)} = \text{constant!}$$

Adopted values:

- $\zeta \sim 10^{-17} \text{ s}^{-1}$ (derived from observations)
- $f \sim \frac{1}{2}$ (inferred from models)
- $k_e \sim 2 \times 10^{-7} \text{ cm}^3 \text{ s}^{-1}$ (measured in lab)
- $n(\Sigma H)/n(\Sigma C) \sim 10^4$ (cosmic abundance)

$n(H_3^+)$ is constant $\sim 10^{-7} \text{ cm}^{-3}$ which is independent of the density of the cloud!
Much to our surprise, the Galactic Center sources IRS 3 (shown above) and GCS 3-2 show deep H$_3^+$ absorptions. In the case of IRS 3, both a narrow and a broad component was observed. Since the line of sight to the Galactic Center crosses both dense and diffuse clouds, it is difficult to separate the two contributions to the H$_3^+$ absorption.

\[
\begin{align*}
N_{\text{para}} &= 5.1(1.7) \times 10^{14} \text{ cm}^{-2} \\
N_{\text{ortho}} &= 2.4(1.1) \times 10^{14} \text{ cm}^{-2} \\
N_{\text{broad}} &= 17.5(3.9) \times 10^{14} \text{ cm}^{-2}
\end{align*}
\]
Cygnus OB2 Number 12

observed at UKIRT

\[ N_{\text{para}} = 2.4(3) \times 10^{14} \text{ cm}^{-2} \]
\[ N_{\text{ortho}} = 1.4(2) \times 10^{14} \text{ cm}^{-2} \]

Similar column density to dense clouds!!
About Cygnus OB2 #12

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- $d \sim 1.7$ kpc
- $l \sim 80^\circ$, $b \sim 0^\circ$
- $A_V \sim 10$ mag
- $N(H) \sim 2 \times 10^{22}$ cm$^{-2}$
- $M_V \sim -10$ mag!
- spectral type B5Ie
- stellar wind $\sim 1400$ km/s
- no 3.08 $\mu$m ice feature $\Rightarrow$ no dense clouds
- strong 3.4 $\mu$m C-H band $\Rightarrow$ diffuse clouds
- CH, C$_2$ observations suggest $n \sim 300$ cm$^{-3}$

Morgan, Johnson, & Roman
PASP 66, 85 (1954)
This spectrum of CO in absorption was obtained using CGS4 at UKIRT. The low column density, \( N(\text{CO}) \sim 10^{16} \text{ cm}^{-3} \), compared with \( N(\text{H}) \sim 10^{22} \text{ cm}^{-3} \), suggests that only about 1% of carbon is in the form of CO. This eliminates the possibility that the \( \text{H}_3^+ \) absorption is due to dense clouds.
These millimeter-wave spectra of CO, taken with the James Clerk Maxwell Telescope (JCMT) show CO at velocities -21, +7, and +12 km/s. The -21 km/s component is probably behind the source. The +7 and +12 km/s components are in agreement with the infrared CO and H$_3^+$ absorption spectra.
For Cygnus OB2 No. 12, the observed column density is \( N(H_3^+) = 3.8 \times 10^{14} \text{ cm}^{-2} \) and the predicted number density is \( n(H_3^+) \sim 10^{-7} \text{ cm}^{-3} \).

**Path Length:**

\[
L \sim \frac{N(H_3^+)}{n(H_3^+)} \sim \frac{3.8 \times 10^{14} \text{ cm}^{-2}}{10^{-7} \text{ cm}^{-3}} \sim 3.8 \times 10^{21} \text{ cm} \sim 1 \text{ kpc!}
\]

**Density:**

\[
[H_2] \sim \frac{N(H_2)}{L} \sim \frac{2 \times 10^{22} \text{ cm}^{-2}}{3 \times 10^{21} \text{ cm}} \sim 10 \text{ cm}^{-3}
\]

**Problem:**

1 kpc is over \( \frac{1}{2} \) the distance to star!

⇒ expect \( H_3^+ \) “everywhere”

⇒ barely consistent with linewidth

**Solutions?:**

⇒ \( \zeta \) may be too low?

⇒ \( k_e \) may be too high?

⇒ maybe it’s true??

**Upcoming Observations:**

⇒ higher spectral resolution

(constrain linewidth)

⇒ nearby objects

(spatial extent of \( H_3^+ \))

⇒ other diffuse cloud sources

(maybe this is a fluke?)