H$_3^+$ in Diffuse Interstellar Clouds: A Tracer for the Cosmic-Ray Ionization Rate

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Motivations

• $\text{H}_3^+$ is the cornerstone of ion-molecule reactions in the interstellar medium (ISM)
• Simple chemistry allows for the inference of various physical parameters (density, temperature, ionization rate, cloud size)
Observations

adapted from McCall et al. (1999)

CGS4 spectrometer on the United Kingdom Infrared Telescope (UKIRT)

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Atmospheric Interference

- complex of CH$_4$ lines centered at 36675.3 Å reduces transmission to about 50%
- various HDO lines also crowd the region and cut transmission to about 80%
- H$_3^+$ lines only have about 1-2% absorption, so a high S/N is necessary
Detections

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Non-detections
Relating column density to cosmic-ray ionization rate

- **Formation pathway**
  - $\text{CR} + \text{H}_2 \rightarrow \text{CR} + \text{H}_2^+ + \text{e}^-$
  - $\text{H}_2 + \text{H}_2^+ \rightarrow \text{H}_3^+ + \text{H}$

- **Destruction mechanism**
  - $\text{H}_3^+ + \text{e}^- \rightarrow \text{H}_2 + \text{H}$ or 3H

- Using the steady-state approximation we obtain...

\[
 n(\text{H}_2) \zeta_2 = k_e n(\text{H}_3^+) n(\text{e})
\]

\[
 n(\text{H}_3^+) = \frac{N(\text{H}_3^+)}{L} \quad f = \frac{2n(\text{H}_2)}{n_H}
\]

\[
 n_H = n(\text{H} \text{ I}) + 2n(\text{H}_2)
\]

\[
 \zeta_2 = N(\text{H}_3^+) \frac{k_e}{L} \frac{2}{f} \frac{n(\text{e})}{n_H}
\]
Variables & Assumptions

\[ \zeta_2 = N(H_3^+) \frac{k_e 2 n(e)}{L f n_H} \]

- \( N(H_3^+) \) is measured
- \( k_e \) is known from experiments (\( \sim 10^{-7} \text{ cm}^3 \text{ s}^{-1} \))
- \( n(e)/n_H \) is relatively constant in diffuse clouds (\( 1.4 \times 10^{-4} \) assuming electrons come from ionized carbon)
- 2 is certainly still 2

- \( f \) can be approximated using measured H I and H\(_2\) column densities

\[ L = N_H/n_H \]
- \( N_H \) can be measured or estimated from \( E(B-V) \)
- \( n_H \) is estimated in various ways (C I levels, C\(_2\) levels, \( J=4 \) level of H\(_2\))

- \( \zeta_2 = 2.3 \zeta_p \)

\[ \zeta_p = \frac{2}{2.3} N(H_3^+) \frac{n_H}{f} \frac{k_e}{N_H} \left[ \frac{n(e)}{n_H} \right] \]
# Results

<table>
<thead>
<tr>
<th>Object</th>
<th>( N(\text{H}_3^+) ) ((10^{14} \text{ cm}^{-2}))</th>
<th>( \zeta_p ) ((10^{-16} \text{ s}^{-1}))</th>
<th>Object</th>
<th>( N(\text{H}_3^+) ) ((10^{14} \text{ cm}^{-2}))</th>
<th>( \zeta_p ) ((10^{-16} \text{ s}^{-1}))</th>
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<tr>
<td>HD 20041</td>
<td>1.6</td>
<td>2.9</td>
<td>HD 21483</td>
<td>&lt; 2.2</td>
<td>&lt; 5.7</td>
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<td>HD 21389</td>
<td>1.0</td>
<td>1.8</td>
<td>40 Per</td>
<td>&lt; 0.9</td>
<td>&lt; 2.6</td>
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<tr>
<td>ζ Per</td>
<td>0.7</td>
<td>3.2</td>
<td>ε Per</td>
<td>&lt; 0.5</td>
<td>&lt; 2.4</td>
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<tr>
<td>X Per</td>
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<td>3.1</td>
<td>ζ Per</td>
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<td>&lt; 4.5</td>
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<td>HD 169454</td>
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<td>0.9</td>
<td>62 Tau</td>
<td>&lt; 2.7</td>
<td>&lt; 14</td>
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<td>HD 229059</td>
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<td>2.9</td>
<td>o Sco</td>
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<td>&lt; 0.9</td>
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<td>BD -14 5037</td>
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<td>0.5</td>
<td>W40 IRS 1a</td>
<td>3.4</td>
<td>1.5</td>
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<td></td>
<td></td>
<td></td>
<td>HD 147889</td>
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<td>&lt; 1.6</td>
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<tr>
<td>WR 104</td>
<td>2.3</td>
<td>1.4</td>
<td>ζ Oph</td>
<td>&lt; 0.3</td>
<td>&lt; 1.5</td>
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<tr>
<td>WR 118</td>
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<td>2.0</td>
<td>HD 168625</td>
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<td>&lt; 0.8</td>
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<tr>
<td>WR 121</td>
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<td>1.7</td>
<td>λ Cep</td>
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<td>&lt; 1.3</td>
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<tr>
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<td>&lt; 1.3</td>
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<td>P Cyg</td>
<td>&lt; 0.6</td>
<td>&lt; 1.2</td>
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</tbody>
</table>

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Cosmic-Ray Ionization Rates: Measured and Modeled

\[ \zeta_p \left(10^{-16} \text{ s}^{-1}\right) \]

<table>
<thead>
<tr>
<th>ζ Per</th>
<th>ι Per</th>
<th>ε Per</th>
<th>ζ Per</th>
<th>ζ Oph</th>
<th>Reference</th>
<th>Method</th>
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<tr>
<td>3.2</td>
<td>&lt;5.0</td>
<td>&lt;2.4</td>
<td>&lt;4.5</td>
<td>&lt;1.5</td>
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<td>H_3^+</td>
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<td>0.22</td>
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<td>0.06</td>
<td>0.17</td>
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<td>1.30</td>
<td>…</td>
<td>≤0.26</td>
<td>…</td>
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<tr>
<td>1-2</td>
<td>≥8</td>
<td>…</td>
<td>…</td>
<td>≥4</td>
<td>van Dishoeck &amp; Black (1986)</td>
<td>models</td>
</tr>
<tr>
<td>5.2</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
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<td>H_3^+</td>
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<tr>
<td>2.5</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>…</td>
<td>Le Petit et al. (2004)</td>
<td>models</td>
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</table>
Possible Explanations for Differences

- smaller value of $k_e$ used in the past
- charge transfer $\text{H}^+$ to $\text{O}$ is endothermic
- grain neutralization ‘removes’ $\text{H}^+$
- $N(\text{D I})/N(\text{H I})$ overestimates deuterium fraction $n_D/n_H$
Conclusions

- $\text{H}_3^+$ is common and abundant in diffuse interstellar clouds.
- Due to its simple chemistry, $\text{H}_3^+$ can be used to infer the cosmic-ray ionization rate $\zeta_p$ in diffuse clouds is relatively constant and an order of magnitude larger than previously believed.
Future Prospects

• Observing run at UKIRT June 29-July 2 to re-visit 4 sightlines and investigate 4 new sightlines
• 36 hours in January at UKIRT to get better S/N on Perseus sources
• Proposal submitted for time on Gemini South in December to investigate the diffuse ISM in the Large Magellanic Cloud
Acknowledgments

- UKIRT staff
- NSF
- References

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