The Interstellar Chemist's Most Insightful Tool: H_3^+ Observed in a Variety of Astronomical Environments

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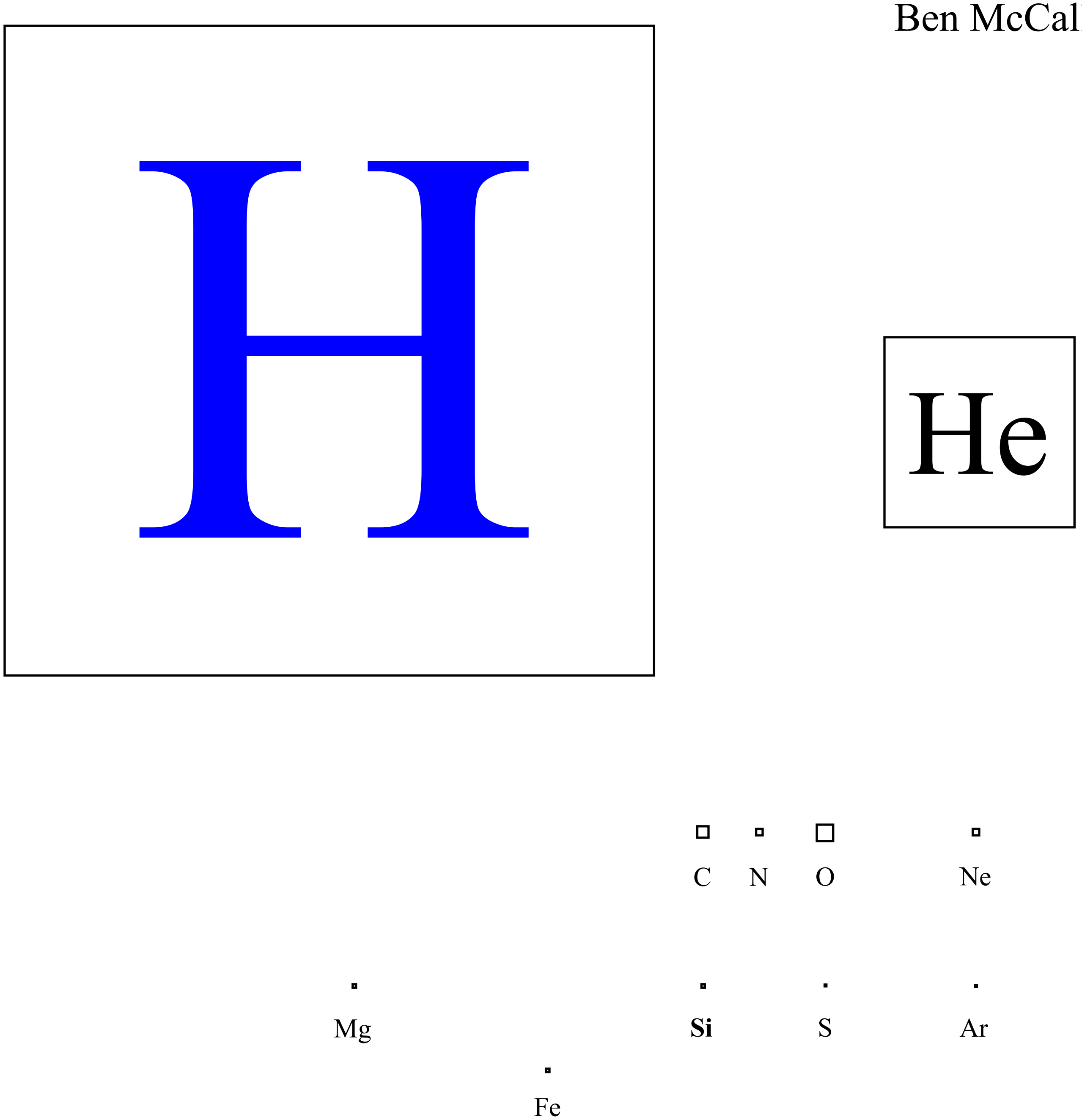
The Astronomer’s Periodic Table

Ben McCall



Chemistry of H_3^+

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Simple Formation Mechanism

$$\text{cosmic ray} + H_2 \rightarrow H_2^+ + e^- \quad \text{(slow)}$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H \quad \text{(fast)}$$

Simple Destruction Mechanisms

$$H_3^+ + CO \rightarrow HCO^+ + H_2 \quad \text{(if CO abundant)}$$

$$H_3^+ + e^- \rightarrow H_2 + H \quad \text{(if } e^- \text{ abundant)}$$

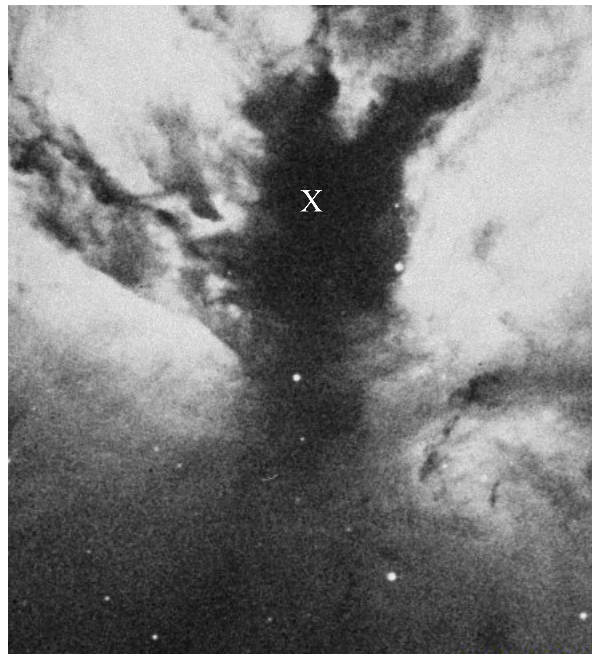
Simple Chemistry $\Rightarrow$ Easy Interpretation

Dense Interstellar Clouds

Ben McCall

Physical Environment:

- ★ gas density ~ 10^4 cm^{-3}
- ★ temperature ~ 10-30 K
- ★ shrouded in dust
- ★ starlight is blocked



The Dense Cloud NGC 2024

Chemical Environment:

- ★ $H \rightarrow H_2$ (photolysis blocked by gas and dust)
- ★ $C \rightarrow CO$ — network of complicated chemistry
- ★ CO is most abundant molecule (next to H_2)
- ★ $[H_2]/[CO] \sim 10^4$

H_3^+ in Dense Clouds

Ben McCall

$$\text{Formation Rate} = \zeta\,[H_2]$$

$$\text{Destruction Rate} = k_{CO}[CO][H_3^+]$$

$$\text{Steady State} \rightarrow \zeta\,[H_2] = k_{CO}[CO][H_3^+]$$

$$[H_3^+] = \frac{\zeta}{k_{CO}}\frac{[H_2]}{[CO]}$$

$$= \frac{(3\times10^{-17}\,s^{-1})}{(2\times10^{-9}\,cm^3 s^{-1})}\cdot 10^4 \cong 10^{-4}\,cm^{-3}$$

H_3^+ in Dense Clouds

Ben McCall

H_3^+ observed column density

$$N(H_3^+) = \int [H_3^+]\, dx \cong [H_3^+] \cdot L$$

$$\therefore L = \frac{N(H_3^+)}{[H_3^+]} = \frac{N(H_3^+)}{10^{-4}\,\mathrm{cm}^{-3}}$$

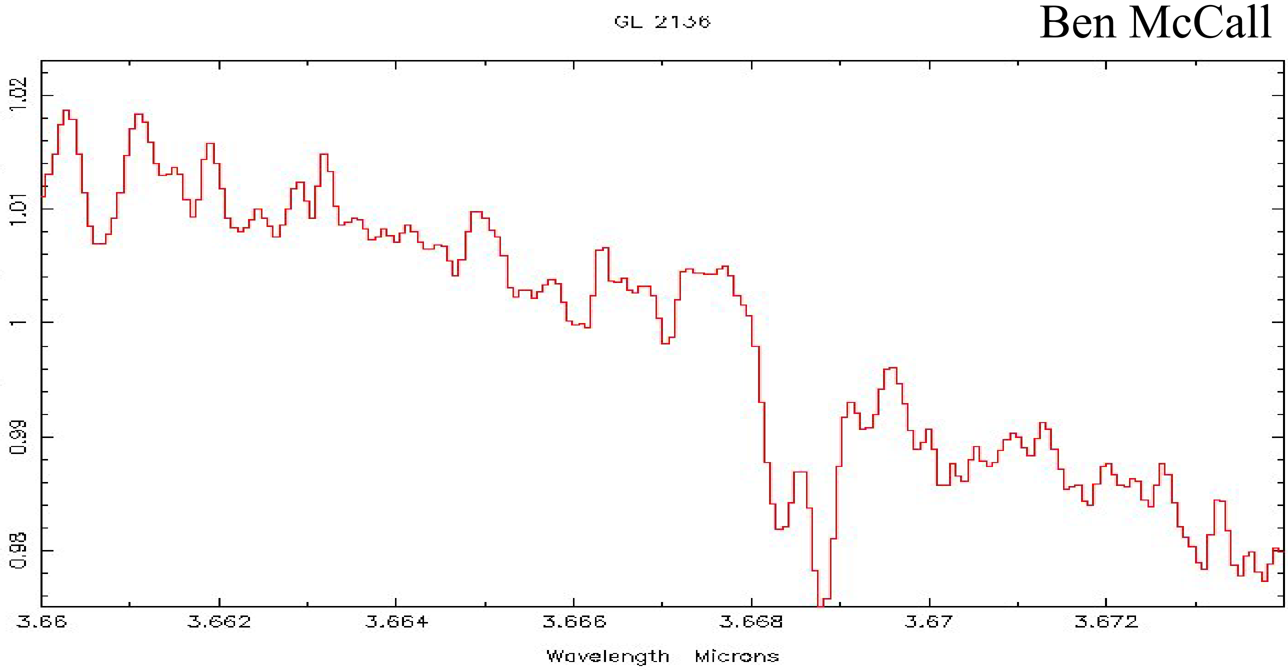
Inferred H_2 column density

$$N(H_2) \cong [H_2] \cdot L$$

$$\therefore [H_2] = \frac{N(H_2)}{L} = \frac{10^{-4}\ \mathrm{cm}^{-3} \cdot N(H_2)}{N(H_3^+)}$$

Dense Cloud — GL 2136

Ben McCall



$$N(H_3^+) = 4 \times 10^{14}\,\text{cm}^{-2}$$

$$L \approx 1.2 \times 10^{19}\,\text{cm} \approx 4\text{pc} \approx 800{,}000\ \text{AU}$$

$$[H_2] \approx \frac{1.8 \times 10^{23}\,\text{cm}^{-2}}{1.2 \times 10^{19}\,\text{cm}} \approx 1.5 \times 10^{4}\,\text{cm}^{-3}$$

$$T \approx 35\ \text{K}$$

Diffuse Interstellar Clouds

Ben McCall

Physical Environment:

★ gas density ~ 100 cm^{-3}

★ temperature ~ 30-100 K

★ starlight penetrates

★ carbon is ionized

Chemical Environment:

★ $f \equiv \frac{[H_2]}{[H]+2[H_2]} \approx \frac{1}{4}$

★ $C \rightarrow C^+ + e^-$ (ionized by incident starlight)

★ $[\Sigma H]/[\Sigma C] \sim 10^4$

H_3^+ in Diffuse Clouds

Ben McCall

$$\text{Formation Rate} = \zeta\,[H_2]$$

$$\text{Destruction Rate} = k_e\,[e^-][H_3^+]$$

$$\text{Steady State} \rightarrow \zeta\,[H_2] = k_e\,[e^-][H_3^+]$$

$$[H_3^+] = \frac{\zeta}{k_e}\frac{[H_2]}{[e^-]} \approx \frac{\zeta}{k_e}\frac{\frac{1}{4}[H]}{[C]}$$

$$= \frac{(3\times10^{-17}\,s^{-1})\cdot\frac{1}{4}}{(2\times10^{-7}\,cm^3 s^{-1})}\cdot10^4 \simeq 10^{-6}\,cm^{-3}$$

H_3^+ in Diffuse Clouds

Ben McCall

H_3^+ observed column density

$$N(H_3^+) = \int [H_3^+]\, dx \cong [H_3^+] \cdot L$$

$$\therefore L = \frac{N(H_3^+)}{[H_3^+]} = \frac{N(H_3^+)}{10^{-6}\,\mathrm{cm}^{-3}}$$

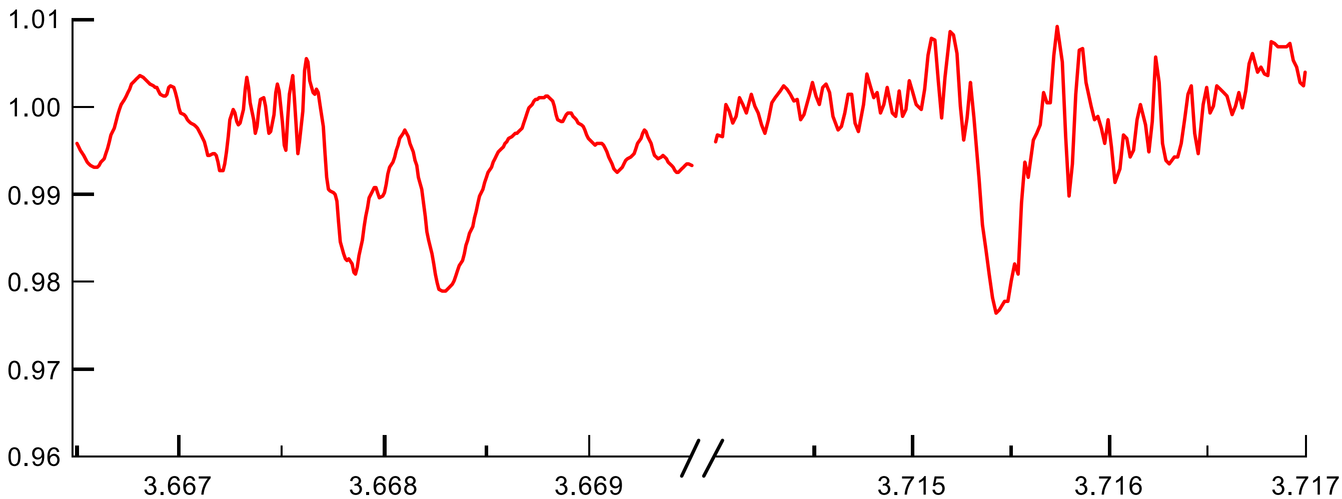
Inferred H column density

$$N(H) \cong [H] \cdot L$$

$$\therefore [H] = \frac{N(H)}{L} = \frac{10^{-6}\,\mathrm{cm}^{-3} \cdot N(H)}{N(H_3^+)}$$

Diffuse Cloud — VI Cyg 12

Ben McCall



$$N(H_3^+) = 4 \times 10^{14}\,\mathrm{cm}^{-2}$$

$$L \approx 3 \times 10^{20}\,\mathrm{cm} \approx 100\mathrm{pc} \approx 2 \times 10^{7}\ \mathrm{AU}$$

$$[H] \approx \frac{1.5 \times 10^{22}\,\mathrm{cm}^{-2}}{3 \times 10^{20}\,\mathrm{cm}} \approx 50\,\mathrm{cm}^{-3}$$

$$T \approx 20\ \mathrm{K}$$

Summary

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- ★ H_3^+ is a most insightful tool
  - ★ "easily" observable hydrogenic species
  - ★ simple formation & destruction mechanisms
  - ★ provides temperature, path length, density
  - ★ cornerstone of interstellar chemistry
- ★ H_3^+ in a variety of environments
  - ★ dense clouds: GL 2136, W33A, GL 961E, MonR2 IRS 3, GL 2591
  - ★ diffuse clouds: VI Cyg 12, ...?
  - ★ Galactic Center: GC IRS 3, Quint 24, ...?
  - ★ what's next??