A Brief History of Chemistry in the Cosmos

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Outline

Let there be light
\[ H^- + H \rightarrow H_2 + e^- \]
Motivation
D1 Experiment
Results

Let there be life
\[ C + H_3^+ \rightarrow \text{COMs} \]
Motivation
D3 Experiment
Results
Science is answering questions that humanity has pondered for millennia.
Let there be light

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Results
Structure formation in the early universe

Gravity

Cloud cools by $\text{H}_2$ radiation $T \rightarrow 200 \text{ K}$

As volume decreases temperature increases

$\text{H}_2$ (.01%) $\text{He}$ (0.9)

$\text{Li}$ ($10^{-10}$)
How $\text{H}_2$ radiatively cools the gas down to temperature of $T \sim 200$ K
H$_2$ Formation during Epoch of Protogalaxy and First Star Formation

Associative detachment (AD)

$$H^- + H \rightarrow H_2 + e^-$$

This was not well understood before we started.
Published kinetics for $\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}^-$

There is nearly an order of magnitude spread. This has significant cosmological implications!
First Star Formation

Upper limit for stellar mass set by balance of outward pressure and inward gravitational force.

This hydrostatic equilibrium limit is commonly called the Jeans mass:

\[ M_J \propto \frac{T^{3/2}}{\sqrt{n}} \]

Uncertainties in \( M_J \) translate into uncertainties in predicted elemental yield from nucleosynthesis.
Implications for First Star Formation

- Initially ionized gas
- 3D simulation.
- Curves is for limits of $\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}^-$ rate coefficient.
- $M_J \propto T^{3/2}n^{-1/2}$
- $M_J$ uncertain by factor of 20.

(Kreckel et al. 2010, Science, 329, 69)
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\[ \text{C} + \text{H}_3^+ \rightarrow \text{COMs} \]

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The apparatus the day after first signal

\[ H_2^+ \rightarrow H_2 \rightarrow H_2^+ \]

Detachment

Form \( H_2 \)

Laser
How much did this cost?

A) $10,000
B) $100,000
C) $1,000,000
D) $10,000,000
How much did this cost?

C) $735,548
The Team Members

K. A. Miller, H. Bruhns, DWS, X. Urbain, H. Kreckel
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Kinetics data for $\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}^-$
Adding in our results

Theory and experiment have finally converged.
Implications for First Star Formation

- Initially ionized gas
- 3D simulation.
- Red & black due to previous AD uncert.
- Other points show new ±25% uncert.
- $M_J$ uncertainty goes from 20 to 2!

(Kreckel et al. 2010, Science, 329, 69)
Questions on First Half of Talk?
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Results
Pathway from atoms in space to life on Earth is full of unknowns.

How far did interstellar chemistry take us on this pathway towards life?
The interstellar medium exhibits a rich chemistry. 200+ molecules have been found. 3/4ths contain carbon (C). Interstellar chemistry is organic in nature. There’s water there too.
Some gas-phase pathways for forming the chemicals needed for life

Conditions in dense molecular clouds:
\[ n \sim 10^4 \text{ cm}^{-3} \]
\[ T_{\text{gas}} \sim 10 \text{ K} \]

\[
\begin{align*}
&\left[ \text{H}_2 \right] \rightarrow \text{H}_3^+ + \text{C} \\
&\text{H}_3^+ + \text{C} \rightarrow \text{CH}_n^+ + \left\{ \text{H} \text{CNO} \right\} \\
&\left\{ \text{H} \text{CNO} \right\} \rightarrow \text{carboxyl cyano amino}
\end{align*}
\]
Published kinetics of $\text{C} + \text{H}_3^+ \rightarrow \text{CH}^+ + \text{H}_2$

QM calc’s beyond current theoretical abilities. No lab data exist at molecular cloud temperatures. Over factor of 2 uncertainty in the rate coefficient.
Let there be light

$H^- + H \rightarrow H_2 + e^-$

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Let there be life

$C + H_3^+ \rightarrow \text{COMs}$

Motivation

D3 Experiment

Results
We have built an apparatus to study

\[ C + H_3^+ \rightarrow CH_n^+ + H_{3-n} \]
IT'S QUIZ TIME
How much did this cost?

A) $1,000,000
B) $2,000,000
C) $4,000,000
D) $8,000,000
How much did this cost?

B) $1,999,242
The Team Members

Ken Miller, X. Urbain, DWS, Jule Stützel, A. O’Connor, Nathalie de Ruette
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Let there be light

H⁻ + H → H₂ + e⁻

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C + H₃⁺ → COMs

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Results
$C + H_3^+$ summed thermal rate coefficients

Reduced uncertainty from factor of $>2$ to $<20\%$.
New C + H$_3^+$ data reduces abundance uncertainties in astrochemical models

Log(Max/Min) vs Log(time [yrs])


489 species shown

Old

Factor of 2
New C + H$_3^+$ data reduces abundance uncertainties in astrochemical models.


489 species shown

Log(Max/Min) vs. Log(time[yrs])

Old

Factor of 2

New
Conclusions

• We have performed the first energy dependent measurements for the $\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}^-$ reaction.

• Our results will improve cosmological models for protogalaxy and first star formation.

• Have developed a new apparatus to study astrochemical reactions with atomic D, C, and O.

• We have measured $\text{C} + \text{H}_3^+$, $\text{O} + \text{H}_3^+$, as well as $\text{D} + \text{H}_3^+/\text{H}_2\text{D}^+/\text{D}_2\text{H}^+$.

• Results improve our understanding of the chemical evolution of the cosmos.
Thanks for your attention.