Cosmic Evolution, Part II
Heavy Elements to Molecules
First a review of terminology:

- **Element**
  - Atom
  - Electrons
  - Nucleus
  - Electromagnetic
  - Protons
  - Neutrons
  - Strong Nuclear

- **Compound**
  - Molecule
  - Electromagnetic

**Neutral atom:**
- # Electrons = # protons

**Ion:**
- e.g. \( \text{C}^{+2} \)
- Carbon nucleus + 4 (6-2) electrons
H atom

Forces

Molecule: Repulsive ~ Attractive

More delicate than atoms, can be much more complex
“Bond” is sharing of electrons
Is molecule stable?
Yes, if EM potential energy less than separate atoms

Activation energy lower $\rightarrow$ $T \sim 100 - 1000$ K
(Room Temperature)
Questions

• Why is room temperature around 300 K?
• How commonly is this temperature found in the Universe?
Conventions:

- $H_2$  \( H - H \)
- $CO_2$  \( O = C = O \)

Bond

Double Bonds

Maximum # of Bonds:

- H 1
- O 2
- N 3
- C 4

Carbon very versatile

→ Complex chemistry
Interstellar Molecules

Exist as gas (individual molecules)
A few known in 1930’s
Many more since 1968 - Radio astronomy

Rotation

Vibration

Radio Telescope

Infrared Telescope
**Appendix 2**

**Interstellar Molecules**

<table>
<thead>
<tr>
<th>Species</th>
<th>Name</th>
<th>Species</th>
<th>Name</th>
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<tr>
<td>H₂</td>
<td>molecular hydrogen</td>
<td>CO₂</td>
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<td>magnesium isocyanide*</td>
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<td>HCO₂</td>
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<td>N₃⁺</td>
<td>protonated nitrogen</td>
<td>CH₃CN</td>
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<td>H₂N</td>
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<td>N₂O</td>
<td>nitrous oxide</td>
<td>CH₄</td>
<td>methane</td>
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* Detected in circumstellar envelopes only
† tentative

**Species** | **Name**
--- | ---
H₂COH⁺ | protonated formaldehyde
SiH₄ | silane*
C₄Si | *
C₅ | pentatomic carbon*
C₅H | pentanylydine
C₅N | ethylene*
C₅H₄ | ethylene
H₂C₅C₆ | butatrienyldiene
CH₃OH | methanol
CH₃CN | methyl cyanide
CH₃NC | methyl isocyanide
CH₃SH | methyl mercaptan
NH₂CHO | formamide
HC₃HO | propionaldehyde
HC₃NH⁺ | propionaldehyde
CH₃C₆NH | cyanobenzonitrile
C₆H | cyanoxydipropyl

**Species** | **Name**
--- | ---
HC₃N | cyanodiacetylene
CH₃H | methyl formate
CH₃C₆N | methylcyanoacetyle
CH₃COOH | acetic acid
H₂C₆ | vinyle
CH₂OCHO | glycolaldehyde
H₂C₅OH | ethanol
CH₃C₆H | methyldiacetylene
CH₃C₆H₂ | dimethyl ether
CH₃C₆H₂CN | ethyl cyanide
CH₃C₆H₂OH | ethanol
HC₇N | cyanobenzonitrile
C₈H | cyanohexatriyne

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Look at Appendix 2
This is an old version
Important Examples:

Water \( \text{H}_2\text{O} \)

Ammonia \( \text{NH}_3 \)

Formaldehyde \( \text{H}_2\text{CO} \)

Others of Note:  CO  Most common after \( \text{H}_2 \)

HCN, HC\(_3\)N, … HC\(_{11}\)N → Carbon chains

CH\(_4\)  (Methane)

PAHs (Polycyclic aromatic hydrocarbons)
3 Lessons

1. Complexity (Up to 13 - atoms) is extraterrestrial
   May be more complex (Hard to detect)
   Glycine claimed in 1994, but, so far, not confirmed
   Polycyclic Aromatic Hydrocarbons (PAHs)
   (Infrared evidence)

2. Dominance of Carbon
   Carbon Chemistry not peculiar to Earth

3. Formation & Destruction  Analogous to early Earth
   Destruction:
   Ultraviolet light breaks bonds
   Massive Stars
   Protection by dust grains: scatter and absorb ultraviolet
Dust particles

Studies of how they scatter and absorb light
(Ultraviolet $\rightarrow$ Visible $\rightarrow$ Infrared)

$\Rightarrow$ Two types, range of sizes up to $10^{-6}$ m

Carbon  Silicates
PAHs $\rightarrow$ Soot $\quad$ Si + O + Mg, Fe, ...

Both Produced by old stars
Formation of Interstellar Molecules

1. $\text{H}_2$
   Must lose the potential energy difference before it falls apart ($\sim 10^{-14}$ s)
   Collisions: OK in lab, too slow in space

   Emit photon: very slow for $\text{H}_2$ ($10^7$ s)

   $\text{H} + \text{H} + \text{catalyst} = \text{H}_2 + \text{catalyst}$

   Surface of dust grain
Formation of Interstellar Molecules

2. More complex molecules
   Problem is activation energy barrier
   \[ T \sim 10 \text{ K} \ll \text{Barrier} \]
   Use reactions \textbf{without} activation energies
   e.g. Molecular ions, like \( \text{HCO}^+ \)

\[
\begin{align*}
\text{Cosmic Ray} & \quad \rightarrow \quad \text{Energy} + \text{simple mol.} \\
\text{H}_2^+ + \text{H}_2 & \rightarrow \text{H}_3^+ + \text{H} \\
\text{H}_3^+ + \text{CO} & \rightarrow \text{HCO}^+ + \text{H}_2 \\
\text{XH}^+ + e^- & \rightarrow \text{X} + \text{H}
\end{align*}
\]

\[ \rightarrow \text{Reactive mol.} \quad \downarrow \quad \text{More complex} \]
Ion - Molecule Reactions

Neutral Molecule

Molecule or atom

Electromagnetic Potential Energy

Separation of Ion and Molecule

No Barrier!
Molecules on Dust Grains

Infrared observations show this: as molecules vibrate, absorb infrared

- e.g. \( \text{H}_2\text{O} \) absorbs at \( 3 \times 10^{-6} \text{ m} \)
- \( \text{CH}_4 \) absorbs at \( 8 \times 10^{-6} \text{ m} \)
Ices on Dust Grains
Implications

1. Similar (Carbon-Dominated) Chemistry

2. Direct Role in Origin of Life?

3. Formation + Destruction analogous to Early Earth

Roles of Dust

1. Protection from UV
2. $\text{H}_2$ Formation
3. Freeze-out $\rightarrow$ Mantles of Ice
   \[
   \text{H}_2\text{O}, \text{NH}_3, \text{CH}_4, \text{CO}_2, \text{HCOOH}, \ldots
   \]
   
   \[
   \uparrow
   \]
   
   Methane
Star Formation

First factor in Drake Equation: The rate of star formation
Estimate of Average Star Formation Rate ($R_*$)

$$R_* = \frac{\text{# of stars in galaxy}}{\text{lifetime of galaxy}} = \frac{N_*}{t_{\text{gal}}}$$

$N_* : \text{ Count them? No}$

Use Gravity (Newton’s Laws)

Sun orbiting center of galaxy at 270 km s$^{-1}$ (167 miles per second)

Kinetic energy = \frac{1}{2} \text{ gravitational potential energy}

$$\frac{1}{2} M_\odot v^2 = \frac{1}{2} \frac{G M_g M_\odot}{R_g}$$

Distance of Sun from center of galaxy

$$\frac{R_g v^2}{G} = M_g$$
Estimate of Average Star Formation Rate ($R_\star$)

($R_g = 28,000$ ly) $\rightarrow M_g = 1.4 \times 10^{11} M_\odot$

Add mass outside Sun’s orbit $\rightarrow M_g \sim 4.6 \times 10^{11} M_\odot$

Most is dark matter; Models indicate $8 \times 10^{10}$ $M_\odot$ in stars

$N_* \sim \frac{M_g}{\text{Avg. mass of star}} = \frac{8 \times 10^{10}}{0.5} = 16 \times 10^{10}$

$ t_{\text{gal}} \sim 10^{10}$ yr (studies of old stars)

$R_\star \sim \frac{16 \times 10^{10}}{10^{10}}$ stars $= 16$ stars per year

Current rate: 4 stars per year
Making an Estimate

16 stars per year is an average over history of Milky Way. Current rate is about 4 stars per year. Stars formed more rapidly early in history of Milky Way. Stars at least as old as the Sun are better candidates for intelligent life. Any number between 5 and 20 may be correct for our purposes, but understand the way we estimated it and the uncertainties.
Star Formation

Current Star Formation
Molecular Clouds

• Composition
  – H$_2$ (93%), He (6%)
  – Dust and other molecules (~1% by mass)
    • CO next most common after H$_2$, He
• Temperature about 10 K
• Density (particles per cubic cm)
  – ~100 cm$^{-3}$ to 10$^6$ cm$^{-3}$
  – Air has about 10$^{19}$ cm$^{-3}$
  – Water about 3 x 10$^{22}$ cm$^{-3}$
• Size 1-300 ly
• Mass 1 to 10$^6$ M$_{\text{Sun}}$
A Small Molecular Cloud
Current Star Formation

• Occurs in gas with heavy elements
  – Molecules and dust keep gas cool
  – Radiate energy released by collapse
  – Stars of lower mass can form
  – Mass needed for collapse increases with $T$

• Star formation is ongoing in our Galaxy
  – Massive stars are short-lived
  – Star formation observed in infrared
Visible to Infrared Views
Artist’s Conception

Features:
- Dusty envelope
- Rotation
- Disk
- Bipolar outflow

R. Hurt, SSC
The Protostar

- Evolution of the collapsing gas cloud
  - At first, collapsing gas stays cool
  - Dust, gas emit photons, remove energy
  - At $n \sim 10^{11} \text{ cm}^{-3}$, photons trapped
  - Gas heats up, dust destroyed, pressure rises
  - Core stops collapsing
  - The outer parts still falling in, adding mass
  - Core shrinks slowly, heats up
  - Fusion begins at $T \sim 10^7 \text{ K}$
  - Protostar becomes a main-sequence star
Summary

- Cosmic evolution builds complexity to molecules and dust
- Energy + simple things leads to complexity
- Stars form in clouds of molecules and dust
- We have estimates for the first factor in the Drake Equation, $R_*$
- Understand the arguments used to get this estimate