Interstellar molecules

- About two hundreds gas-phase molecular species have been detected so far
- Besides simple molecules with a few atoms, also complex molecules with a relatively large number of atoms have been detected

http://www.astro.uni-koeln.de/cdms/molecules

- Observational bias:

  Different types of molecules are observed in different types of interstellar or circumstellar regions
  Some of them are only observed in dense molecular clouds
  Symmetric molecules are harder to detect: they could be more abundant than what observed

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Small interstellar molecules

- Found in diffuse molecular clouds
  - molecular clouds with relatively low extinction
- Large molecules are absent in diffuse clouds because of:
  - physical conditions
    - diffuse clouds are less protected from interstellar radiation field than denser molecular clouds
  - observational limitations
    - diffuse clouds have relatively low column densities and this fact makes hard to detect large molecules, characterized by a low abundance

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TABLE 1  
Interstellar and circumstellar molecules as compiled by Al Wootten (see text)

| Number of Atoms | Number | Species | Method | Target | N/σ
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>2</td>
<td>H₂</td>
<td>UV</td>
<td>C/Opk</td>
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<td>3</td>
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<td>C/Per</td>
<td>5.1 (± 0.4)</td>
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<tr>
<td>12</td>
<td>CH</td>
<td>Optical</td>
<td>C/Opk</td>
<td>1.5 (± 0.9)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>CH⁺</td>
<td>Optical</td>
<td>C/Opk</td>
<td>2.4 (± 0.9)</td>
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<tr>
<td>14</td>
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<td>C/Opk</td>
<td>3.5 (± 10)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>CN</td>
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<td>C/Opk</td>
<td>6.2 (± 10)</td>
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<tr>
<td>17</td>
<td>CN</td>
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<td>C/Opk</td>
<td>9.1 (± 9)</td>
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<td>C/Opk</td>
<td>1.9 (± 9)</td>
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<td>27</td>
<td>HCN</td>
<td>mmabs</td>
<td>BL, Lw</td>
<td>2.6 (± 9)</td>
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<td>8.4 (± 10)</td>
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<td>HD 123184</td>
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<td>UV</td>
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<tr>
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<td>1.5 (± 9)</td>
<td></td>
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<td>HOC⁺</td>
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<td>8.9 (± 9)</td>
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<tr>
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<td>X/Per</td>
<td>7.4 (± 10)</td>
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</tr>
<tr>
<td>30</td>
<td>CO²⁻</td>
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<td>X/Per</td>
<td>2.1 (± 9)</td>
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<td>36</td>
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<tr>
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<td>HCl</td>
<td>UV</td>
<td>C/Opk</td>
<td>3.9 (± 10)</td>
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<td>38</td>
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<td>BL, Lw</td>
<td>8.4 (± 10)</td>
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<tr>
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<td>CS</td>
<td>mmabs</td>
<td>BL, Lw</td>
<td>1.6 (± 9)</td>
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<td>64</td>
<td>SO₂</td>
<td>mmabs</td>
<td>BL, Lw</td>
<td>0.2 (± 19)</td>
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</tr>
</tbody>
</table>

Note: All molecules with a large number of atoms are organic. Atoms with low cosmic abundance are only detected in small molecules.
Complex interstellar molecules
(“complex” for interstellar standards, not for chemists)

- Complex interstellar molecules are hydrocarbons
- They are found in:
  - star-forming regions
  - circumstellar envelopes of evolved, late-type stars in the Asymptotic giant branch (AGB)
  - dense clouds in the direction of the Galactic center

Herbst & van Dishoeck (2009)

Examples of interstellar hydrocarbons

<table>
<thead>
<tr>
<th>Species</th>
<th>Name</th>
<th>Source</th>
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<tbody>
<tr>
<td>C₂H₂</td>
<td>Ethene</td>
<td>ciso</td>
</tr>
<tr>
<td>HC₅H</td>
<td>Butadiene</td>
<td>ciso</td>
</tr>
<tr>
<td>H₂C₃</td>
<td>Butadiene</td>
<td>ciso, c, l</td>
</tr>
<tr>
<td>C₃H₄</td>
<td>Propadiene</td>
<td>ciso, c</td>
</tr>
<tr>
<td>C₃H₅</td>
<td>Heteropropadiene</td>
<td>ciso, c, l</td>
</tr>
<tr>
<td>C₄H₆</td>
<td>Butatriene</td>
<td>ciso, c, l</td>
</tr>
<tr>
<td>C₅H₇</td>
<td>Heteropentadiene</td>
<td>ciso, c, l</td>
</tr>
<tr>
<td>C₆H₈</td>
<td>Hexatriene</td>
<td>ciso</td>
</tr>
<tr>
<td>C₆H₉</td>
<td>Heterohexadiene</td>
<td>ciso, c, l</td>
</tr>
<tr>
<td>C₇H₈</td>
<td>Heptatriene</td>
<td>ciso</td>
</tr>
<tr>
<td>C₈H₁₀</td>
<td>Octatriene</td>
<td>ciso, l</td>
</tr>
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<td>C₉H₁₁</td>
<td>Nonatriene</td>
<td>ciso, c</td>
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<tr>
<td>C₁₀H₁₂</td>
<td>Decatriene</td>
<td>ciso, c</td>
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<td>C₁₁H₁₃</td>
<td>Undecatriene</td>
<td>ciso, c</td>
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<tr>
<td>C₁₂H₁₄</td>
<td>Dodecatriene</td>
<td>ciso</td>
</tr>
<tr>
<td>C₁₃H₁₅</td>
<td>Tridecatriene</td>
<td>ciso, c</td>
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<tr>
<td>C₁₄H₁₆</td>
<td>Tetradecatriene</td>
<td>ciso, c</td>
</tr>
<tr>
<td>C₁₅H₁₇</td>
<td>Pentadecatriene</td>
<td>ciso, c</td>
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<tr>
<td>C₁₆H₁₈</td>
<td>Hexadecatriene</td>
<td>ciso, c</td>
</tr>
<tr>
<td>C₁₇H₁₉</td>
<td>Heptadecatriene</td>
<td>ciso, c</td>
</tr>
<tr>
<td>C₁₈H₂₀</td>
<td>Octadecatriene</td>
<td>ciso, c</td>
</tr>
</tbody>
</table>

Saturation of interstellar organic molecules

- Saturated hydrocarbons
  - The chain of carbon atoms are held by single bonds
  - The remaining carbon bonds are saturated with hydrogen atoms
- Interstellar organic molecules are usually not saturated
  - Example of saturated molecule not detected in the ISM
    Cyclohexane, C₆H₁₂
  - Example of unsaturated molecule detected in the ISM
    Benzene, C₆H₆

Formamide
An interstellar molecule of prebiotic interest

Detected multiple rotational transitions in the sub-millimetric spectral range in molecular clouds at different locations in the Galaxy

Adande et al. (2013)
Complex organic molecules in the interstellar medium

- Glycolaldehyde ($\text{C}_2\text{H}_4\text{O}_2$)
  - Simplest sugar
  - First intermediate product of the reaction which starts with formaldehyde ($\text{H}_2\text{CO}$) and leads to the formation of various sugars and finally of ribose, one of the DNA building blocks

\[
\begin{align*}
\text{O} & \quad \text{C} \quad \text{H} \\
\text{CH}_2\text{OH} & 
\end{align*}
\]

Generic formula for sugars $C_n(\text{H}_2\text{O})_n$

- Detection of glycolaldehyde ($\text{CH}_2\text{OHCHO}$)
  - First detection of interstellar sugar
  - Detected in the millimetric band towards Sagittarius B2(N), a source in the direction of the Galactic center (Hollis et al. 2000)
  - Also observed by ALMA around a young, solar-type star

Complex organic molecules in the interstellar space

The case of glycine

- Glycine is the simplest aminoacid found in biological proteins ($\text{NH}_2\text{CH}_2\text{COOH}$)
  - Its existence in the interstellar space would demonstrate the existence of chemical pathways potentially able to synthesise basic ingredients of life molecules in the interstellar space
  - The “lateral group” R is simply a hydrogen atom

Conventional depiction of aminoacids

Tentative evidence for interstellar glycine

- Glycine ($\text{NH}_2\text{CH}_2\text{COOH}$)
  - Several emission lines attributed to interstellar glycine have been reported
    - Kuan et al. (2003)
  - The identification is not confirmed by a subsequent analysis performed by testing a larger number of lines expected for glycine
    - Snyder et al. (2005)
Which is the maximum complexity of interstellar organic molecules in the gas phase?

As molecular complexity increases, the identification of the molecule tends to become uncertain.

Gas-phase molecules with a high number of atoms could be present in the interstellar medium, even though it is difficult to prove their existence.

Interstellar dust
The solid phase component of the ISM

Importance of interstellar dust in astronomy

- Effects on astronomical observations
  - Reddening and extinction of astronomical sources
  - Depletion of chemical abundances in the interstellar gas

- Physical effects in the interstellar medium
  - Transformation of UV photons into IR photons
  - Cooling of the ISM by means of thermal emission

- Effects on planetary formation
  - Essential ingredient of planetary formation in protoplanetary

- Importance in astrochemistry
  - Catalyst for the formation of interstellar molecules

Observational evidence of interstellar dust (1)

- Dark regions, dark clouds
  - Absence of stars in large field images
  - Dust grains absorb the optical/UV light of background stars

- In some cases, dark clouds are associated with pre-stellar cores

Observational evidence of interstellar dust (2)
Reflection nebulae

- Dust grains in reflection nebulae scatter the stellar photons

- A detailed study of reflection nebulae provides information on some physical properties of the grains
  - Albedo
    - Ratio between scattering and extinction cross-sections of dust grains
  - Phase function
    - Angular distribution of scattered light
Observational evidence of interstellar dust (3)

Galactic infrared emission

- Thermal emission from interstellar dust
  - Dust is heated by interstellar radiation
  - The infrared emission cools the gas
- Galactic infrared emission maps the distribution of interstellar dust
  1983, IRAS satellite
  - All sky map in the bands at 12, 25, 60 e 100 µm
  - The emission is concentrated in the Galactic plane
  - IR clouds ("cirrus") found outside the Galactic plane

Vibration modes of interstellar solids: ice and dust

A high spectral resolution is required to discriminate between different types of silicates

Pyroxenes: Mg$_{x}$Fe$_{1-x}$SiO$_3$
Olivines: Mg$_2$Fe$_{2+y}$SiO$_4$

Observational evidence of interstellar dust (4)

Infrared absorptions

- Observations of background sources with strong IR emission along lines of sight intersecting dust-rich regions
  - Vibrational bands of solid compounds are detected in absorption
- Ice and organic compounds
  - H$_2$O, CO, CO$_2$, CH$_3$OH ...
- Silicates
  - 9.7 µm e 18 µm
    Streching vibration modes of Si–O bonds
    and bending vibration modes O-Si-O

Examples of silicates
Pyroxenes: Mg$_{x}$Fe$_{1-x}$SiO$_3$
Olivines: Mg$_2$Fe$_{2+y}$SiO$_4$

Observational evidence of interstellar dust (5)

Elemental depletions

Gas-phase interstellar abundances are measured with high-resolution UV spectroscopy
The interstellar (resonance) transitions of the main ionization stages of the most abundant astrophysical elements are found in the UV range
The measurements of interstellar abundances indicate that:
- For most elements the interstellar abundances X/H, measured in the gas phase, are lower than the corresponding solar abundances
- This deficiency is known as "interstellar depletion"
Interstellar depletions

- Interpretation
  a fraction of the atoms is incorporated in dust grains and, as a result, is not counted in the gas-phase column density measurements

- Galactic interstellar depletions are calculated assuming that the total abundance of the interstellar medium (gas plus dust) is solar
  \[ \delta_X = \log_{10} \left( \frac{N_X}{N_H} \right) - \log_{10} \left( \frac{X}{H} \right)_{\text{sun}} \]

  This expression is equal to the definition of \([X/H]\), but the physical meaning is completely different

- Interstellar depletions vary
  - between different elements
  - in different types of interstellar regions

Element-to-element variations of interstellar depletions

- Refractory elements
  - Strong depletions
    e.g., Ti, Ni, Fe, Cr, Mn, ...
- Volatile elements
  - Weak depletions
    e.g., S, Zn
- Correlation between depletion and condensation temperature
  - Empirical evidence that supports the interpretation of depletions in terms of incorporation of a fraction of elements in dust form

Variations of depletions in different types of interstellar regions

- Cold and dense clouds
  - Strong depletions
- Warm and hot gas
  - Weak depletions

- Further evidence that depletions are due to the incorporation of atoms in dust form
  - Dust grains survive (or grow by accretion) in cold and dense clouds
  - Dust grains tend to be destroyed in hot, low density regions

\[ \text{Condensation temperature} \]
Temperature at which the 50% of an element condenses to a solid compound in a cooling gas of solar chemical composition