

Astrochemistry

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1. Introduction

The presence of molecules such as CN, CH, and CH^+ in interstellar space has been known since the late 1930s. More abundant molecular species were identified in subsequent decades. In particular, molecular hydrogen (H_2)—the most abundant molecule not only in interstellar regions but in the entire Universe—was conclusively identified in 1970 through space-based observations by detecting the corresponding ultraviolet Lyman absorption bands in the direction of the star ξ Persei.

Other abundant molecules, including hydroxyl (OH), water vapor (H_2O), ammonia (NH_3), formaldehyde (H_2CO), and carbon monoxide (CO), were detected during the same period via radio observations at millimeter and centimeter wavelengths.

As of 2025, more than 300 molecular species have been identified in the interstellar medium (ISM) (<https://cdms.astro.uni-koeln.de/classic/molecules>). These include molecules containing between 2 and 12 atoms, as well as larger species with more than 12 atoms, such as C_{60} (fullerene) and $\text{C}_{24}\text{H}_{12}$ (coronene), a representative polycyclic aromatic hydrocarbon (PAH).

Molecules have been observed in a wide variety of astrophysical environments, including interstellar clouds, planetary atmospheres, comets, stellar atmospheres and envelopes, Herbig–Haro objects, star-forming regions, H II regions, planetary nebulae, supernova shells and remnants, and active galaxies.

Within the ISM, molecules are primarily concentrated in dense and molecular clouds. They consist predominantly of carbon-bearing hydrides, simple oxides, sulfides, acetylene derivatives, aldehydes, alcohols, ethers, selected cyclic compounds belonging to these families, and radicals. While the majority of detected molecules are neutral, ionic species are also observed, as well as molecules formed from isotopic variants of atoms. For example, CO has been detected in all possible isotopic combinations involving ^{12}C , ^{13}C and ^{16}O , ^{17}O , and ^{18}O .

2. Molecular Spectra

The energy levels of a molecule are primarily determined by three contributions, listed here in decreasing order of energy:

- **Electronic energy**, associated with changes in the electronic quantum number n , producing spectral lines in the ultraviolet and visible regions.
- **Vibrational energy**, associated with changes in the vibrational quantum number ν , giving rise to infrared spectral lines.
- **Rotational energy**, associated with changes in the rotational quantum number J , resulting in spectral lines at millimeter wavelengths.

In general, an observed spectral line may involve simultaneous changes in all three of these quantum numbers.

3. Electronic States

The ground electronic state of a molecule is conventionally denoted by the letter **X**. Excited electronic states that can be reached from the ground state via electric dipole transitions are labeled **A**, **B**, **C**, and so forth. Lowercase letters (**a**, **b**, **c**, etc.) are used to distinguish states of different spin multiplicity from the ground state.

The electronic orbital angular momentum **L** and the electronic spin angular momentum **S** combine vectorially to form the total electronic angular momentum **J** = **L** + **S**, in direct analogy with atomic systems. In a diatomic molecule, the symmetry axis is defined by the line connecting the two nuclei. The projection of the electronic orbital angular momentum onto this axis, denoted **Λ** , is quantized. The corresponding electronic term symbols **Σ** , **Π** , **Δ** , **Φ** , etc., correspond to $\Lambda = 0, 1, 2, 3$, respectively.

As in atomic systems, when $\Lambda \neq 0$ the energy levels are influenced by spin-orbit or related couplings. This arises because the orbital motion of the electrons generates a magnetic field along the internuclear axis, which interacts with the electronic spin magnetic moment. The total electronic spin **S** may take integer or half-integer values and determines the spin

multiplicity of the level. Specifically, there are $2S + 1$ possible values of the spin projection M_s along the symmetry axis (often denoted by Σ).

The projection of the total electronic angular momentum onto the internuclear axis is therefore given by

$$\Omega = |\Lambda + \Sigma|.$$

Accordingly, the electronic state of a diatomic molecule is commonly written as $^{(2S+1)}\Lambda_{\Omega}$, although the Ω subscript is frequently omitted when it is not explicitly required.

Two additional symbols describe the symmetry properties of the electronic wave function. For Σ states, the superscripts “+” or “−” indicate whether the wave function remains unchanged or changes sign, respectively, upon reflection in a plane containing the internuclear axis. The subscripts “g” (gerade, even) and “u” (ungerade, odd) describe the behavior of the wave function under inversion through the molecular center of mass, provided the molecule consists of identical atoms.

3.2 Vibrational States

In a molecule, the nuclei oscillate relative to one another under the influence of an interatomic potential. For low-energy levels, this potential closely resembles that of a simple harmonic oscillator, while at higher energies it becomes increasingly anharmonic and ultimately leads to molecular dissociation. Each vibrational state is characterized by the vibrational quantum number v .

More complex molecules (for example, CO_2) may possess additional vibrational degrees of freedom, which are denoted by ν_1 , ν_2 , ν_3 , and so forth. As an illustration, in the CO_2 molecule—where the carbon atom is located at the center and the oxygen atoms at the ends—there are three fundamental vibrational modes: two stretching modes and one bending mode.

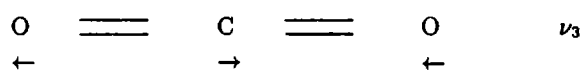
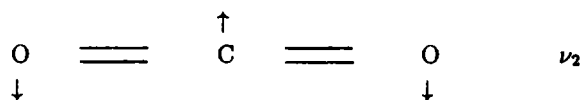
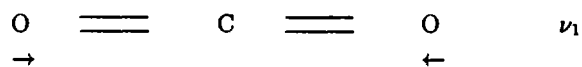


Figure 1. Vibrational modes of CO₂: the **v₁** mode (wavelength 7.22 μm) and **v₃** mode (4.27 μm) correspond to stretching vibrations, while the **v₂** mode (14.97 μm) corresponds to a bending vibration.

The energy of a vibrational level can be approximated as the sum of harmonic oscillator energies.

$$E_V = \left(v_1 + \frac{1}{2}\right)h\nu_1 + \left(v_2 + \frac{1}{2}\right)h\nu_2 + \left(v_3 + \frac{1}{2}\right)h\nu_3 + \dots$$

A vibrational state is specified by the corresponding set of quantum numbers (**v₁, v₂, v₃, ...**).

3.3 Rotational States

Classification of Molecules According to Their Moments of Inertia

Molecules are classified according to their moments of inertia. From top to bottom, the classes are: **linear molecules, symmetric tops, spherical tops, and asymmetric tops.**

$I_A = 0, I_B = I_C \neq 0$	Linear molecule	CO ₂ , N ₂ O, O ₂ , N ₂ , CO
$I_A \neq 0, I_B = I_C \neq 0$	Symmetric top	NH ₃
$I_A = I_B = I_C$	Spherical top	CH ₄
$I_A \neq I_B \neq I_C$	Asymmetric top	H ₂ O, O ₃

Figure 2. Classification of molecules according to the values of their moments of inertia.

Rotational energy is the smallest of the three principal contributions to a molecule's total energy. Rotating molecules are divided into four classes according to the values of their moments of inertia (Figure 2). The rotational angular momentum is quantized and described by the rotational quantum number **J**.

3.3.1 Linear Molecules

Dipole radiation is possible only if a molecule possesses a permanent electric dipole moment. Homonuclear molecules, such as H₂, lack a permanent dipole moment and can emit radiation only through highly improbable transitions. Similarly, CO₂ does not exhibit a pure rotational spectrum.

In contrast, CO possesses a pure rotational spectrum, which is of great importance in the millimeter wavelength range as a tracer of cold molecular gas. The $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of both ^{12}CO and ^{13}CO are widely used in the mapping of molecular clouds.

The rotational energy levels of a linear molecule are proportional to $J(J + 1)$, with a small correction due to centrifugal distortion resulting from molecular stretching. Nuclear symmetry in linear molecules can be classified as either “a” (antisymmetric) or “s” (symmetric).

The rotational selection rule is

$$\Delta J = 0, \pm 1,$$

with the transition $J = 0 \rightarrow J = 0$ forbidden.

3.3.2 Spherical Tops

Due to the absence of a unique symmetry axis, spherical top molecules possess rotational energy levels identical to those of linear molecules. The only difference lies in the statistical weights of the energy levels.

3.3.3 Symmetric Top Molecules

For symmetric top molecules, the component of the rotational angular momentum along the symmetry axis is quantized and characterized by the quantum number K . The quantum number K is an integer, positive, and satisfies $K \leq J$. A pure rotational transition is therefore specified by the initial and final values of J and K .

Symmetric top molecules are classified as **prolate** (elongated) if $A > B$, and **oblate** (flattened) if $A < B$. The rotational energy levels are given by

$$E = BJ(J + 1) + (A - B)K^2,$$

where A and B are the rotational constants, which are inversely proportional to the corresponding moments of inertia I_A and I_B

The rotational selection rules are

$$\Delta K = 0, \Delta J = 0, \pm 1,$$

with the transition $J = 0 \rightarrow J = 0$ forbidden.

3.3.4 Asymmetric Top Molecules

Asymmetric top molecules represent an intermediate case between prolate and oblate symmetric tops. In this case, K ceases to be a useful quantum number. A rotational state characterized by the quantum number J is split into $2J + 1$ distinct energy levels.

The rotational selection rule is

$$\Delta J = 0, \pm 1,$$

with the transition $J = 0 \rightarrow J = 0$ forbidden.

Since the rotational energy is no longer a monotonic function of J , all three values of ΔJ correspond to positive energy transitions in absorption spectra. These transitions are traditionally classified as:

- $\Delta J = -1$: *P branch*
- $\Delta J = 0$: *Q branch*
- $\Delta J = +1$: *R branch*

3.3.5 Example 1: The Water Molecule (H₂O)

In the water molecule, the spins of the two hydrogen nuclei may be either parallel or antiparallel. As a result, two nuclear spin isomers are distinguished: **ortho-water** (parallel spins) and **para-water** (antiparallel spins), which typically occur in a statistical ratio of **3:1**.

The vibrational spectrum of water consists of three normal modes, ν_1 , ν_2 , and ν_3 . The lowest-frequency mode is the bending mode ν_2 , at **1595 cm⁻¹** (6.25 μm). The other two modes, ν_1 and ν_3 , correspond to wavelengths of **2.74 μm** and **2.66 μm** , respectively.

3.3.6 Example 2: Molecular Hydrogen (H₂)

The electronic ground state of the molecular hydrogen molecule is

$$X^1\Sigma_g^+$$

Here, **X** denotes the ground electronic state, **1** indicates the spin multiplicity (i.e., **S = 0**), **Σ** signifies that the projection of the electronic orbital angular momentum onto the symmetry axis is zero, and the remaining symbols describe the symmetry properties of the electronic wave function.

4. Molecular Hydrogen in Interstellar Clouds

The most abundant molecule in interstellar space is molecular hydrogen, H₂. It constitutes a significant fraction of diffuse clouds and accounts for nearly the entire mass of dense molecular clouds. Hydrogen, both in atomic and molecular form, is strongly correlated with the presence of dust grains. As will be shown below, molecular hydrogen is formed most efficiently on the surfaces of dust grains.

Formation of Molecular Hydrogen in the Gas Phase

The formation of H₂ in the gas phase requires the collision of two hydrogen atoms in a cloud with hydrogen number density **n_H** and temperature **T**. The typical thermal velocity of hydrogen atoms is

$$v_H \sim \sqrt{kT/m_H} \quad (1)$$

where *k* is the Boltzmann constant and *m_H* is the hydrogen atom mass.

For molecule formation, two atoms must approach each other within a distance *d*. Assuming a collision cross section of order **πd^2** , one may estimate the characteristic collision time

$$t_c \sim \frac{1}{\pi d^2 n_H v_H}. \quad (2)$$

Taking representative values ***d* ≈ 3 Å**, **T ≈ 100 K**, and **n_H ≈ 10⁴ cm⁻³**, one finds

$$t_c \approx 10^7 \text{ yr.}$$

Even for the densest clouds ($n_H \approx 10^7 \text{ cm}^{-3}$), the collision time remains of order

$$t_c \approx 10 \text{ yr.}$$

These timescales are very long, indicating that gas-phase formation of molecular hydrogen is extremely inefficient. Consequently, the corresponding chemical reactions are slow compared to those occurring in very dense environments, such as the Earth's atmosphere.

Formation of Molecular Hydrogen on Dust Grains

To remove the excess energy released during molecule formation following atomic collisions, a third body is required. The surface of a dust grain can serve this role, allowing the newly formed molecule to stabilize. The rate of H_2 formation can be estimated from the collision rate between hydrogen atoms and dust grains.

Consider spherical dust grains of radius a and number density n_d . The available surface area per unit volume for collisions is $\pi a^2 n_d$, while the flux of hydrogen atoms is $n_H v_H$. The formation rate of molecular hydrogen per unit volume and per unit time is therefore

$$\frac{dn_{H_2}}{dt} \sim \frac{1}{2} \pi a^2 n_d n_H v_H, \quad (3)$$

where the factor **1/2** accounts for the random orientation of atomic velocities.

This estimate assumes that all hydrogen atoms colliding with dust grains stick to the surface and efficiently form H_2 molecules. More realistic treatments include adsorption efficiencies and formation probabilities.

Using representative average values

$$a \approx 1000 \text{ \AA} = 10^{-5} \text{ cm}, n_d/n_H \sim 10^{-11}, T \sim 100 \text{ K}, v_H \sim 10^5 \text{ cm/s},$$

one obtains, to order of magnitude, we obtain an order-of-magnitude accuracy

$$\frac{dn_{H_2}}{dt} \sim 10^{-16} n_H^2 \text{ cm}^{-3} \text{ s}^{-1}.$$

For example, for $n_H \sim n_{H_2} \sim 10^2 \text{ cm}^{-3}$, this rate yields

$$dn_{H_2}/dt \sim 10^{-12} \text{ cm}^{-3} \text{ s}^{-1}$$

Photodissociation of Molecular Hydrogen

Molecular hydrogen is destroyed primarily at the edges of interstellar clouds through absorption of ultraviolet radiation. This absorption effectively shields molecules located deeper within the cloud from photodissociation.

If the column density is small, $N(H_2) \leq 10^{14} \text{ cm}^{-2}$, the photodissociation rate is high, approximately

$$\sim 10^{-10} \text{ s}^{-1},$$

and the medium remains predominantly atomic rather than molecular.

This threshold column density can also be derived from the photodissociation cross section of molecular hydrogen in the Lyman bands,

$$\sigma(H_2) \approx 10^{-14} \text{ cm}^2.$$

The optical depth is given by

$$\tau \simeq \sigma(H_2) N(H_2).$$

Requiring $\tau \lesssim 1$ immediately yields

$$N(H_2) \lesssim 10^{14} \text{ cm}^{-2}.$$

In denser environments, the photodissociation rate decreases roughly inversely with column density. Once $N(\text{H}_2) \geq 10^{16} \text{ cm}^{-2}$, the formation rate becomes comparable to the destruction rate, and at even higher column densities molecular hydrogen formation dominates.

In general, efficient molecule formation occurs when the collision frequency τ_c exceeds the evaporation rate τ_e , allowing a hydrogen atom adsorbed on a grain surface sufficient time to encounter another atom and form a molecule:

$$\tau_c > \tau_e.$$

The collision frequency can be estimated as

$$\tau_c \sim \pi a^2 n_H v_H \sim 10^{-3} \text{ s}^{-1}$$

for $T \approx 100 \text{ K}$. Although thermal evaporation is faster, quantum-mechanical considerations show that its timescale is comparable to the collision timescale, allowing molecular hydrogen to form efficiently on dust grain surfaces.

Detection of Interstellar H₂ Molecule

The first detection occurred in the far-ultraviolet (FUV) range, through spectral absorption lines associated with electronic transitions. This means that the corresponding interstellar cloud had to be relatively transparent. To observe denser regions, it is necessary to move to the millimeter (mm) range, involving vibrational and rotational transitions. However, such lines for H₂ are either forbidden or extremely weak. Therefore, other molecules, such as CO, which have sufficiently strong lines in this range, are used instead.

CO and H₂ Molecules in the Interstellar Medium

CO is the second most abundant molecule in molecular clouds, with an abundance relative to H₂ of approximately 10^{-4} . Collisions between these two molecules excite rotational levels, followed by photon emission in the mm range. Such observations allow determination of the molecule's abundance relative to molecular hydrogen, as well as the H₂ content through precise calibration.

Observations of CO emission reveal the brightness temperature profile, $T_b(\nu)$, as a function of the gas radial velocity—or equivalently, the frequency, due to Doppler shift. The CO emission intensity can be expressed as

$$I_{CO} = \int T_b(\nu) d\nu,$$

where the integration is performed over all velocity values for which the emission has been measured. The column density of the molecule can be determined from equation (5) using the known properties of radiative transfer.

Meanwhile, for the column density of H_2 , one can write

$$N_{H_2} = X_{CO} I_{CO},$$

where it is assumed that the value of N_{H_2} is proportional to the CO emission intensity. In equation (5), I_{CO} is measured in K·km/s, so that

$$[X_{CO}] = \text{cm}^{-2} \text{ K}^{-1} (\text{km/s})^{-1}.$$

The necessary calibration to determine X_{CO} is obtained from FUV measurements of H_2 in diffuse clouds, using the relation between neutral and molecular hydrogen and accounting for interstellar extinction. The average value is

$$X_{CO} \sim (1 - 5) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} (\text{km/s})^{-1},$$

and in practice, a value of $4 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} (\text{km/s})^{-1}$ is often used.

For example, along the Galactic plane, where the brightness temperature $T_b(\nu) \simeq 2 \text{ K}$ and is approximately constant over a radial velocity interval $\Delta\nu \sim 20 \text{ km/s}$, we have

$$I_{CO} \sim 40 \text{ km/s and } N_{H_2} \cong 1.6 \cdot 10^{22} \sim 10^{22} \text{ cm}^{-2},$$

Assuming $N_{H_2}/N_{CO} \sim 10^4$, we find

$$N_{CO} \sim 10^{18} \text{ cm}^{-2}.$$

Finally, assuming a typical cloud size of $L \sim 1$ pc, the molecular hydrogen number density is

$$n_{H_2} \sim 10^4 \text{ cm}^{-3}.$$

Where the Absorption Occurs

- **Lyman bands:** 912–1108 Å
- **Werner bands:** 910–1000 Å
- These bands appear as narrow absorption lines superimposed on the UV continuum of background sources.
- Each band is further split into numerous rotational–vibrational lines, labeled by the quantum numbers v (vibrational) and J (rotational).

Example Spectra (Observations)

1. **Copernicus Satellite (1970s):**
 - Provided the first systematic detections of interstellar H₂ absorption.
 - **Reference:** Savage et al. (1977, *ApJS*, 33, 149) — a classic survey of H₂ absorption toward OB stars.
2. **FUSE (Far Ultraviolet Spectroscopic Explorer, 1999–2007):**
 - Delivered high-resolution UV spectra of H₂ absorption in the Milky Way, Magellanic Clouds, and high-redshift systems.
 - **Example:** Tumlinson et al. (2002, *ApJ*, 566, 857) — observations of H₂ in the Magellanic Clouds.
 - The spectra show a series of sharp H₂ absorption lines between 912–1120 Å, often blending with atomic lines (e.g., H I and metals).

Visual Example

Here is a schematic of what the UV spectrum of a hot star with interstellar H₂ absorption looks like:

- The continuum of the hot star is smooth in the far-UV.
- Superimposed on the continuum are many H₂ absorption lines, grouped into the **Lyman** and **Werner bands**.
- **Example figure (from FUSE data):**

- Rachford et al. (2002, *ApJ*, 577, 221): “A FUSE Survey of Interstellar Molecular Hydrogen in Translucent Clouds.”

References

- Savage, B. D., Drake, J. F., Budich, W., & Bohlin, R. C. (1977). *Copernicus survey of H₂ absorption. Astrophysical Journal Supplement Series*, 33, 149.
- Tumlinson, J., et al. (2002). *FUSE study of H₂ in the Magellanic Clouds. Astrophysical Journal*, 566, 857.
- Rachford, B. L., et al. (2002). *A FUSE survey of interstellar molecular hydrogen in translucent clouds. Astrophysical Journal*, 577, 221.
- Draine, B. T. (2011). *Physics of the Interstellar and Intergalactic Medium* (Ch. 6: H₂ electronic absorption)

4. Molecular Reactions in the Gas Phase

The physical conditions of the interstellar medium allow certain chemical reactions to proceed. In the inner regions of molecular clouds, where temperatures are low (5–20 K), only **exothermic reactions**—those accompanied by energy release—can occur, in contrast to **endothermic reactions**, which require an external energy input.

On the other hand, some $C + h\nu \rightarrow C^+ + e^-$ reactions, even if exothermic, require overcoming a **potential (activation) barrier** before the reaction can begin. Thus, if the temperature is sufficiently low that this barrier cannot be overcome, the reaction will not proceed.

The situation is different in regions affected by **photodissociation** and **shock waves**, where temperatures are higher (20–100 K). Under such conditions, reactions with activation barriers become possible, and even some endothermic reactions can take place.

4.1 Ion–Molecule Reactions

In the interstellar medium, ion–molecule reactions are among the most important chemical processes, because the electric charge of one of the reactants acts as an attractive force, facilitating the reaction. For example,

(8)

where the mentioned **photons** or as a result of $\text{H}_3\text{O}^+ + \text{e}^- \rightarrow \text{OH} + \text{H}_2$. ions are produced either by **ionization induced by cosmic radiation**. In molecular clouds, these reactions typically involve the molecular ion H_2^+ , which can initiate the following reactions (9–13).



(9–13)

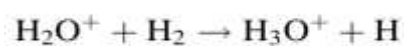
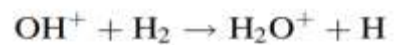
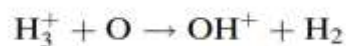
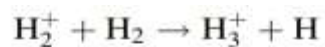
For example, water can be formed via **dissociative recombination** (13). This reaction can alternatively proceed through the formation of **OH**.

(14)

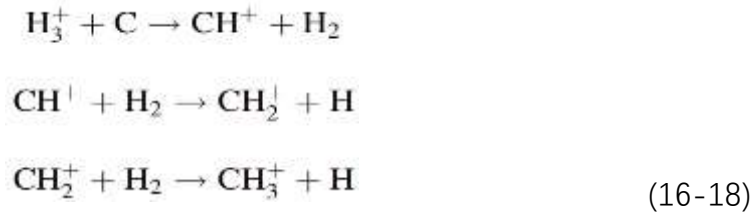
The formation of **H₂O** and **OH** can also occur through the following reaction, which $\text{H}_2 + \text{c.r.} \rightarrow \text{H}_2^+ + \text{e}^- + \text{c.r.}$ is then followed by reactions (11–14).

(15)

The chemistry on **ion-** formation of produced via manner,



of carbon in dense clouds is also based **molecule reactions**, in particular the **CO**. Starting from the ion H_3^+ , which is reaction (9), and proceeding in a similar reactions (10–12) lead to



The formation of **CO** proceeds through the following reactions:

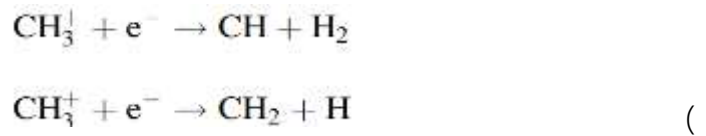


0)

In diffuse clouds, radiation is able to penetrate, leading to the formation of the ion **C⁺**. Through **radiative association** with **H₂**, this ion can then initiate further reactions.



resulting in **CH₂⁺**, which through reactions (18–20) can lead to the formation of either **CH** or **CH₂**.



22-23)

In general, **ion–molecule reactions** are responsible for the formation of the most abundant molecules observed in interstellar clouds, as well as for the synthesis of **long-chain molecules**, such as **HC₉N** and **HC₁₁N**. In a similar way, the participation of the **NH₂** and **NH₃** radicals can lead to the formation of the very important **HCN** molecule.

Neutral–Neutral Reactions

Although less efficient, collisions between neutral atom–atom or atom–molecule pairs can also lead to the formation of new molecules. In this case, the interaction is weaker, and an **energy barrier** may be present that inhibits the reaction. A reaction can proceed if the

colliding particles possess sufficient energy; alternatively, the barrier may be crossed through **quantum-mechanical tunneling**. A few examples are given below.



24-25)

For the first reaction, the activation barrier is negligible, whereas the second reaction is slow at $T \approx 10 \text{ K}$ and becomes faster at $T \approx 300 \text{ K}$, where the barrier plays an important role. The **H₂O** molecule is formed from **neutral oxygen**, which is more abundant than O^+ , the species involved in reaction (15). Thus, water is formed through the following reaction:



This reaction is exothermic but has an activation energy barrier of about 100 K. Such a temperature can occur due to a shock wave, as mentioned above. Endothermic reactions can also take place for the same reason—for example, reactions involving C and H₂ to form hydrocarbons, or N and H₂ to produce ammonia.

Radiative Association

Reactions of the following type are called **radiative association**.



27)

The photon carries away the excess energy, so there is no longer enough energy for dissociation, and the resulting molecule remains stable. Ion–atom and ion–molecule interactions occur through the same mechanism, for example (21).



28)

Radiative Recombination

In this type of reaction, an ion recombines with an electron, emitting a photon. For example, in addition to (15), the O^+ ion can undergo transformation through (29).



29)

Dissociative Recombination

In this type of reaction, a molecular ion recombines with an electron, producing two neutral products.



30-31)

These reactions are faster than radiative recombination. Other examples include (13) and (22–23).

3.6 Charge-Exchange Reaction

In diffuse clouds, the radiation is generally not strong enough to ionize O, but O^+ ions can be produced through the following type of reaction:



32)

Protons are produced through cosmic-ray particles. The resulting oxygen ion, with the help of (15), participates in the formation of water or OH radicals.

3. Molecular Dissociation

In the reactions mentioned above, molecules can also undergo dissociation. In interstellar clouds, the main processes of molecular transformation are photodissociation and collisional dissociation.

3.1 Photodissociation

In diffuse clouds, photodissociation is the primary process responsible for molecular breakdown, for example:



33)

The characteristic timescale for dissociation can be estimated by assuming an interstellar UV flux of $f_\lambda \sim F_\lambda / h\nu \sim 10^5 \text{ photons} \cdot \text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$. The photodissociation cross-section is approximately $\sigma_{ph} \sim 10^{-17} \text{cm}^2$ $\Delta\lambda \sim 100 \text{\AA}$ over a wavelength range. Therefore, the lifetime of a molecule under photodissociation is given by:

$$t_{ph} \sim \frac{1}{f_\lambda \sigma_{ph} \Delta\lambda} \simeq 300 \text{ years.} \quad (34)$$

More precisely, one can define the photodissociation rate, which is formally analogous to the photoionization rate known from the theory of the interstellar medium.

$$\beta_{ph} = c \int n_\lambda \sigma_{ph} d\lambda, \quad (35)$$

where n_λ is the photon number density of the radiation field ($\text{photons} \cdot \text{cm}^{-3} \cdot \text{\AA}^{-1}$), and the integration is carried out from $\lambda = 912 \text{\AA}$ up to the threshold wavelength of the given molecule.

It is assumed here that each absorbed photon leads to molecular dissociation.

Since the photon number density is related to the energy density of the radiation field U_λ ($\text{erg} \cdot \text{cm}^{-3} \text{\AA}^{-1}$),

$$U_\lambda = h\nu n_\lambda = \frac{hc n_\lambda}{\lambda}, \quad (36)$$

We have

$$\beta_{ph} = \frac{1}{h} \int U_\lambda \lambda \sigma_{ph} d\lambda. \quad (37)$$

The photodissociation timescale is given by

$$t_{ph} = \frac{1}{\beta_{ph}} = \frac{h}{\int U_\lambda \lambda \sigma_{ph} d\lambda} \quad (38)$$

At this point, in addition to the properties of the radiation field, it is also necessary to know the wavelength dependence of the process cross section. Clearly, deeper inside the cloud, due to absorption of the radiation, the photodissociation timescale increases, on average by about one order of magnitude for each order of absorption.

3.3. Dissociation due to collisions

In the dense interiors of molecular clouds, the radiation is strongly absorbed and the molecules are largely shielded from radiative effects. Under these conditions, collisions become the dominant dissociation mechanism, for example as a result of increased particle velocities driven by shock waves. These velocities can reach several tens of km/s and may even exceed 100 km/s.

4. Reaction kinetics

In the interstellar medium, thermal processes are generally far from equilibrium. The rates of chemical reactions depend strongly on temperature, density, and a number of other physical parameters that are neither uniform nor constant. Consequently, reactions occurring in the interstellar environment must be treated individually, taking into account as many elementary factors as possible that influence the process.

4.1. Reaction rate

Let us consider the following type of chemical reaction.



39)

Let σ denote the reaction cross section. In that case, the reaction constant (or rate coefficient) k can be defined as follows.

$$k = \langle \sigma v \rangle, \quad ($$

40)

where v is the relative velocity of the interacting reactants. Assuming a Maxwellian velocity distribution, the reaction rate coefficient k depends on the gas temperature. The reaction rate r characterizes the temporal evolution of the concentrations of reactants and products.

$$r = -\frac{dn_A}{dt} = -\frac{dn_B}{dt} = \frac{dn_M}{dt} = \frac{dn_X}{dt}. \quad (41)$$

The reaction rate is always positive and proportional to the reaction rate constant.

$$r = kn_A n_B, \quad ($$

42)

Here, n_A and n_B are the concentrations of reactants A and B. Measuring σ in $[\text{cm}^2]$, v in $[\text{cm/s}]$, and k in $[\text{cm}^3/\text{s}]$, we obtain that r is measured in $[\text{cm}^{-3}\cdot\text{s}^{-1}]$. Reaction rate constants can strongly depend on temperature, particularly in the presence of an energetic activation barrier. For example, in reaction (15), the constant is $k \sim 10^{-9}\text{cm}^3/\text{s}$ per molecule, which corresponds to a cross-section $\sigma \sim 10^{-14}\text{cm}^2$ in an interstellar cloud. Constants of this order are common for a large number of ion–molecule reactions. In the case of neutral–neutral reactions



We obtain $k \sim 10^{-11}\text{cm}^3/\text{s}$ and $\sigma \sim 10^{-15}\text{cm}^2$ at $T \sim 300\text{K}$, i.e., smaller than in ion–molecule reactions. The temperature dependence of the reaction rate constant is often expressed in the form of the classical Arrhenius equation.

$$k(T) = Ae^{-E_a/kT}, \quad (44)$$

where E_a is the activation energy, and A is the Arrhenius factor. From this,

$$\ln k = \ln A - \frac{E_a}{kT}, \quad (45)$$

In this case, the plot of $\ln k$ versus T^{-1} is a straight line, whose slope equals E_a/k , and the y-intercept is at $\ln A$. For example, reaction (26) leads to the formation of the OH radical through the following reaction.



The laboratory values of the constants at different temperatures are shown in Fig. 1.

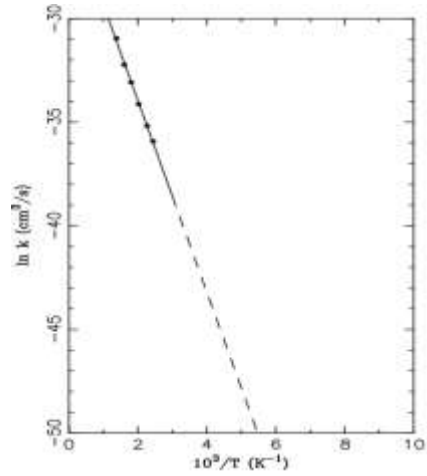


Fig. 1. Reaction rate constants at different temperatures.

Type of reaction	k ($\text{cm}^3 \text{s}^{-1}$)
Ion–molecule reactions	10^{-9}
Neutral–neutral reactions	10^{-11}
Radiative association—diatomic	10^{-17}
Radiative association—polyatomic	10^{-9}
Radiative recombination	10^{-12}
Dissociative recombination	10^{-6}
Charge exchange reactions	10^{-9}

Abundance Calculations

Such estimates can be performed if the reactions involving the given molecule are known. Suppose that the M molecule is formed exclusively according to (39), with a rate constant k_1 . Also, suppose that this molecule is destroyed via photodissociation at a rate of $\beta_M \text{ s}^{-1}$, and ...



47)

with a rate constant k_2 . In this case, over time ...

$$\begin{aligned} \frac{dn_M}{dt} &= k_1 n_A n_B - n_M \beta_M - k_2 n_M n_C \\ &= k_1 n_A n_B - n_M [\beta_M + k_2 n_C]. \end{aligned} \quad (4$$

8)

In the steady-state condition $dn_M/dt = 0$ and

$$n_M = \frac{k_1 n_A n_B}{\beta_M + k_2 n_C}, \quad (49)$$

where n_M is a function of n_A, n_B, n_C , as well as k_1, k_2, β_M . It is necessary to know these quantities and to write the equations (39), (47) for the substances A, B, and C. Thus, the chemistry of interstellar clouds can be studied only if all relevant chemical reactions and their rate constants at different temperatures are known. The problem is extremely complex, involving hundreds of equations, which cannot always be solved with precisely known constants, taking possible instabilities into account.

Results of Observations

5.2 Diffuse Clouds

The results of observations carried out in diffuse clouds, for example in the direction of ς Oph, are presented in Fig. 2.

Atom-molecule	Abundance		
H	1.00	OH	9.2×10^{-8}
H ₂	0.79	CH ⁺	5.5×10^{-8}
O	5.6×10^{-4}	CH	4.8×10^{-8}
C ⁺	1.9×10^{-4}	C ₂	4.8×10^{-8}
N	9.5×10^{-5}	CN	5.0×10^{-9}
C	6.2×10^{-6}	CS	3.0×10^{-9}
CO	3.8×10^{-6}	NH	$< 1.4 \times 10^{-8}$
HD	4.0×10^{-7}	H ₂ O	$< 4.2 \times 10^{-9}$

Fig. 2. Average molecular content in diffuse clouds.

The physical parameters of the cloud are:

$T \sim 20\text{--}60$ K, $n_H \sim 10^2\text{--}10^3$ cm⁻³.

The average column density of neutral hydrogen in the cloud is

$N_H \sim 5.2 \times 10^{20}$ cm⁻².

5.3 Dense Molecular Clouds

In dense (dark) clouds, in contrast to diffuse clouds, the main component is molecular hydrogen. Here, dust plays a dual role in both the protection and formation of molecular hydrogen.

First, the optical depth of dust is sufficiently high to shield the cloud from the destructive effects of interstellar ultraviolet (UV) radiation. Second, the dust grain surfaces act as an efficient medium for molecular synthesis.

Figure 3 presents the observational results related to the Orion Nebula.

Molecule	Abun				
H ₂	1.0	CH ₃ OCH ₃	10 ⁻⁸	HC ₁₂ N	10 ⁻⁹
CO	10 ⁻⁴	CH ₃ CHO	10 ⁻⁸	HNC	10 ⁻⁹
H ₂ O	10 ⁻⁶	OCS	10 ⁻⁸	HCS ⁺	10 ⁻⁹
CH ₃ OH	10 ⁻⁶	CH ₃ C ₂ H	10 ⁻⁸	HC ₅ N	10 ⁻⁹
OH	10 ⁻⁷	SO	10 ⁻⁸	HC ₇ N	10 ⁻⁹
H ₂ CO	10 ⁻⁷	SO ₂	10 ⁻⁸	HC ₉ N	10 ⁻⁹
NH ₃	10 ⁻⁷	CS	10 ⁻⁸	C ₃ N	10 ⁻⁹
CN	10 ⁻⁸	HCO ⁺	10 ⁻⁸	CH ₃ C ₃ N	10 ⁻⁹
C ₂ H	10 ⁻⁸	H ₂ S	10 ⁻⁸	CH ₂ CHCN	10 ⁻¹⁰
HCN	10 ⁻⁸	H ₂ CS	10 ⁻⁹	HNCO	10 ⁻¹⁰
		CH ₃ CN	10 ⁻⁹	PN	10 ⁻¹⁰
				HC ₁₁ N	10 ⁻¹⁰

Fig. 3. Average molecular content in dense clouds: Orion Nebula.

Interstellar Polycyclic Aromatic Hydrocarbons (PAHs)

Early infrared observations, beginning with the IRAS mission, already suggested the presence of aromatic compounds.

Structure. PAH molecules are planar aromatic structures composed of carbon atoms arranged in hexagonal rings, with hydrogen atoms attached at the edges. As an example, the benzene molecule Benzene (C₆H₆) serves as the fundamental building block of aromatic compounds.

Interstellar PAH molecules typically contain 50 or more carbon atoms bonded with hydrogen atoms, reflecting their unsaturated molecular structure.

Such large molecules, or very small dust grains, can undergo transient heating after absorbing an energetic (visible or ultraviolet, UV) photon. Larger dust grains, however, are unable to radiate efficiently due to their low equilibrium temperature.

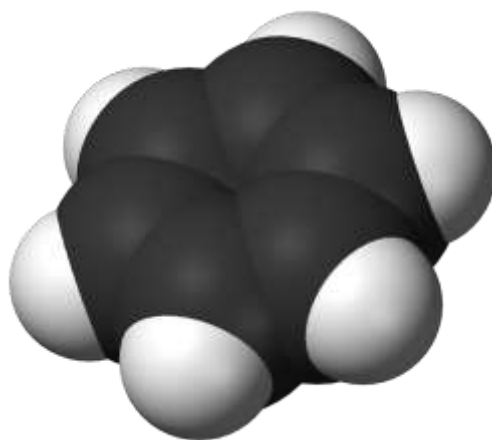


Fig. 4. The Benzene (C_6H_6) molecule.

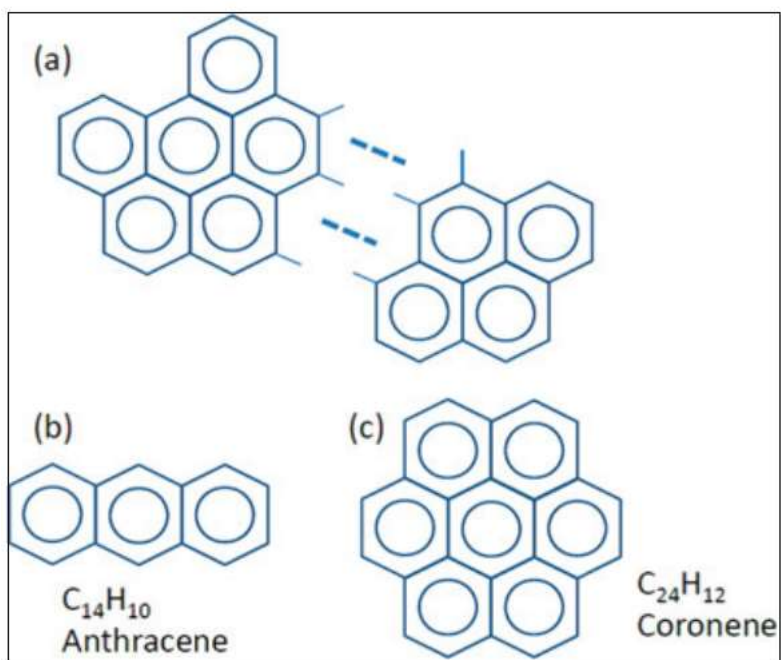


Fig. 4. Different types of polycyclic aromatic hydrocarbons (PAHs).

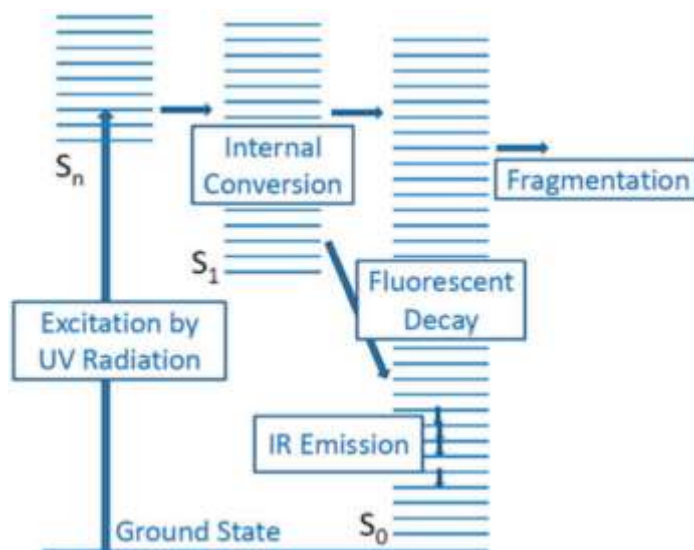


Fig. 5. Schematic representation of the infrared (IR) emission of a PAH molecule after the absorption of a UV photon.

The most important infrared emission bands of PAHs are located at 3.3, 6.2, 7.7, 8.6, and 11.2 μm .

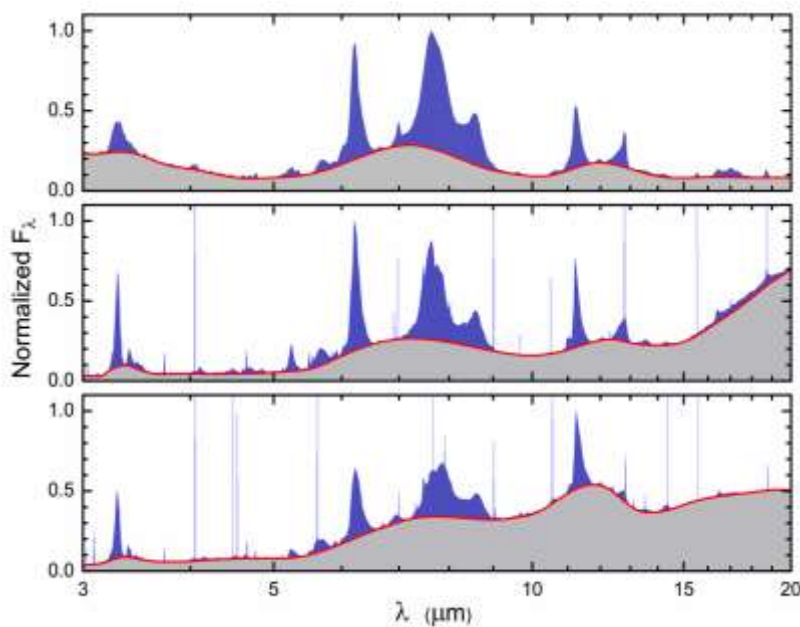


Fig. 6. The most prominent emission bands of a PAH molecule.

They are illustrated in the schematic shown in Fig. 6, while the observed spectrum is presented in Fig. 7.

Some structural characteristics of PAH molecules are given in the Table.

Table.

N_c — number of carbon atoms in the molecule,
 f_c — relative carbon abundance (in ppm, parts per million).

Carrier	Component	N_c	Size (nm)	f_c (ppm)
PAHs	MIR features	20–100	0.4–1	14
PAH clusters	MIR plateaus	100–1000	1–2	8
Small grains	MIR continuum	10^3 – 10^6	2–10	25
Larger grains	FIR continuum	$>10^6$	>10	≥ 35

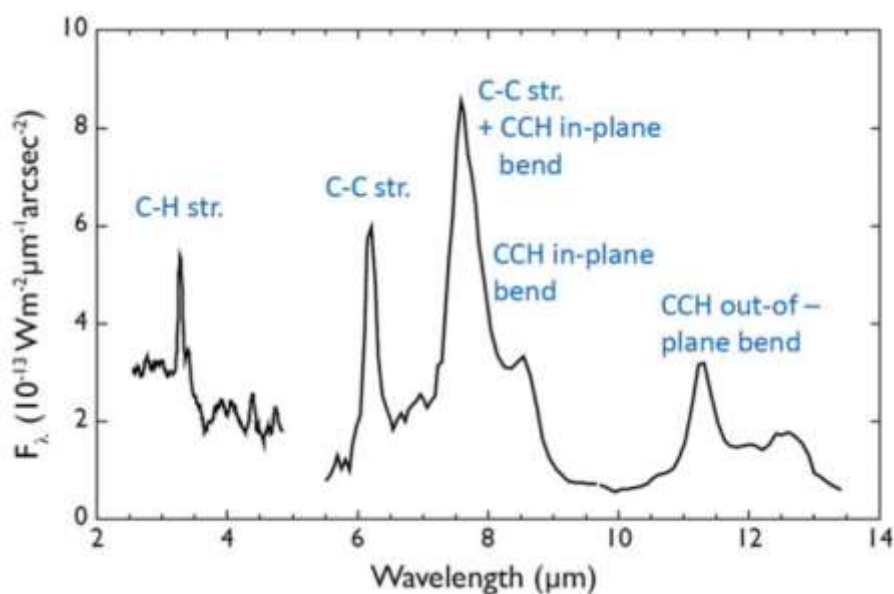
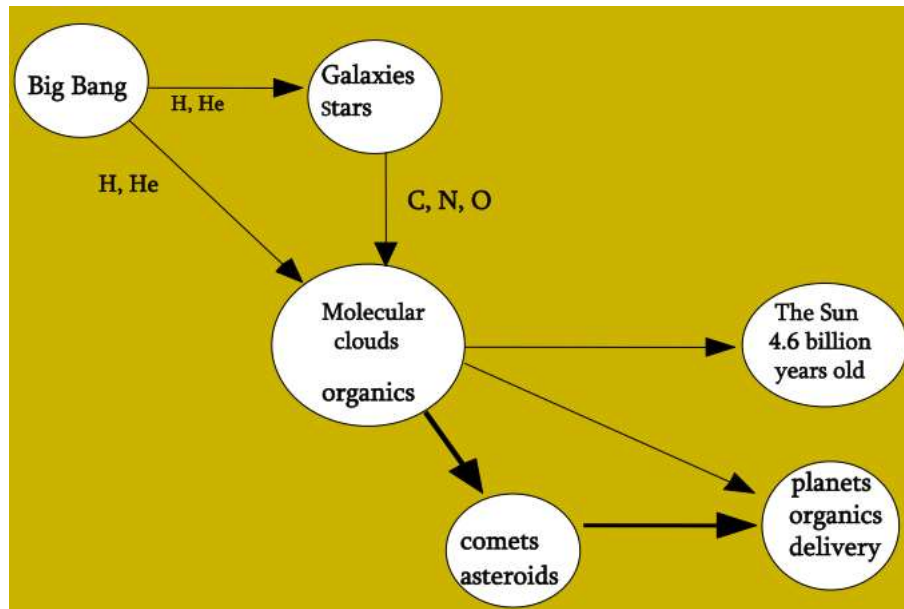


Fig. 7. Infrared (IR) spectrum observed in the Galactic plane (AKARI, Onaka, T. and Sakon, I.)
($l = 312^\circ$, $b = 0.5^\circ$). The main vibrational bands of chemical bonds in the fluctuating spectrum are shown.

Fundamentals of Astrobiology

Apart from Earth, as of 2025, astronomy has not confirmed the existence of life on other planets, including exoplanets. However, observations have already provided substantial insight into how prebiotic molecules could have formed and evolved, eventually leading to the emergence of life on Earth. To clarify our approach, we briefly describe the formation and evolution of such molecules in the Universe. Naturally, we begin with the modern astrophysical understanding of the origin and evolution of the Universe.

According to current data, the Universe originated approximately 13.8 billion years ago.



The beginning, the “zero moment,” is considered a phase transition from an unknown initial state to the state characteristic of the present-day Universe. According to current knowledge, ordinary (baryonic) matter constitutes about 4.9% of the Universe, dark matter about 26.8% (inferred from its gravitational effects), and approximately 68.3% is the so-called dark energy, whose existence follows from the observed accelerated expansion of the Universe.

In the earliest stages, the chemical composition consisted mainly of hydrogen and about ten times less helium. Carbon, oxygen, nitrogen, and heavier elements were synthesized later in the interiors of stars through thermonuclear reactions. These processes produced the full diversity of elements, up to the heaviest elements of the periodic table.

Observational data indicate that the abundances of carbon, nitrogen, and oxygen are about 10,000 times lower than that of hydrogen, while iron-group elements (and biologically important elements such as phosphorus) are about 100,000 times less abundant.

Through supernova explosions (the inevitable end of stars more massive than eight solar masses) and mass loss from lower-mass stars, the interstellar medium becomes enriched with heavy elements necessary for life.

The diffuse interstellar medium gradually condenses into clouds, and in their densest regions—so-called star-forming regions—new stars are born.

It is important to note that the period between about 7 and 5 billion years ago is particularly interesting from the perspective of the emergence of life.

The above-mentioned facts are summarized in the table below:

- ❑ **Decline of intense phenomena in the Universe** — 7–5 billion years ago
- ❑ **Decrease in the star formation rate** — 7–5 billion years ago
- ❑ **Separation of thick and thin galactic disk subcomponents** — 7–5 billion years ago
- ❑ **Intensive dust formation** — dominance of silicate dust (from supernovae) and graphite (carbonaceous) dust (from AGB stars) — 7–5 billion years ago
- ❑ **Increase in velocity dispersion in the galactic disk** (enhanced frequency of star and cloud collisions) — 7–5 billion years ago
- ❑ **Contribution of dark matter condensations** — not yet fully clarified

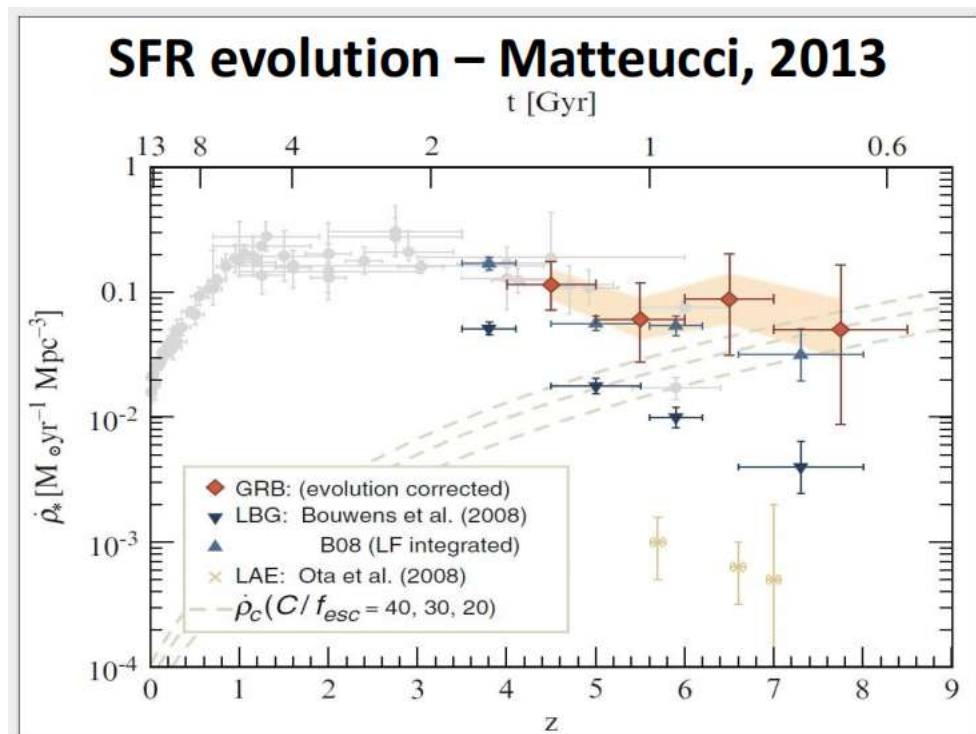


Fig. The decline of the star formation rate over the last 5–7 billion years.

The number of quasars has also decreased over the time elapsed since the Big Bang, as shown in the corresponding figure.

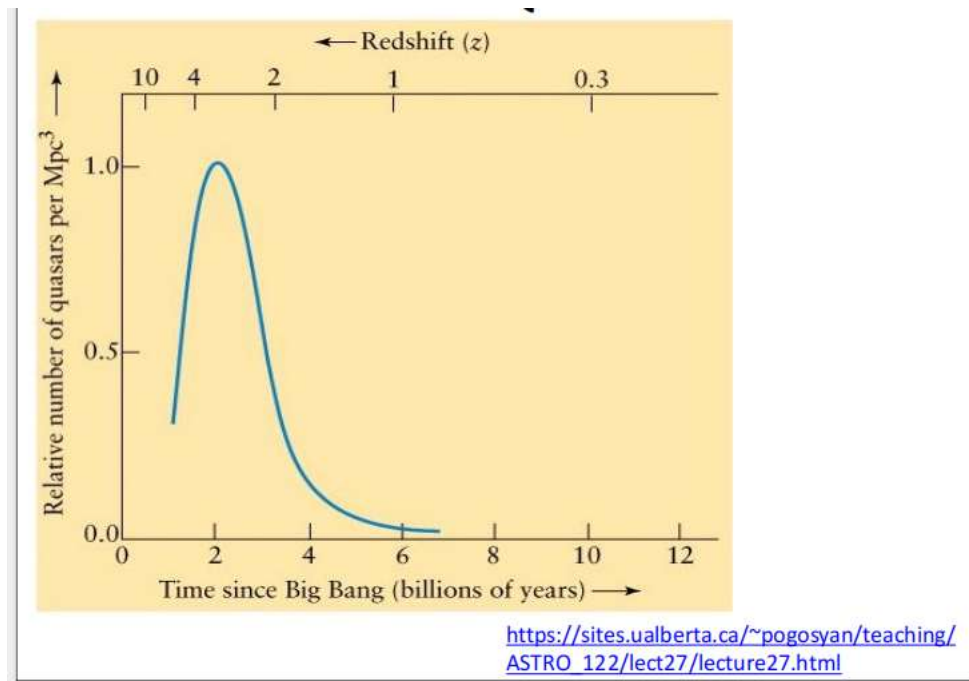


Fig. The decline in the number of quasars per unit volume over time.

Modern science provides the following key chronological data regarding life on Earth:

- The Sun — 4.6 ± 0.1 billion years ago
- The Earth — 4.54 ± 0.05 billion years ago
- End of the cometary bombardment phase on Earth — 3.8 billion years ago (contributing to the formation of the atmosphere and oceans)
- Oldest sedimentary rocks on Earth — 3.8 billion years ago
- First evidence of life on Earth — 3.8 billion years ago
- First cyanobacteria — 2.7 billion years ago
- Significant rise of atmospheric oxygen ($>1\%$) — 2.4 billion years ago

Thus, the Sun formed about 4.6 billion years ago together with its planetary system, including Earth (about 4.5 billion years ago). Most comets and asteroids formed in the vicinity of the giant planets and were later gravitationally scattered both outward and inward, toward the inner planets.

This process lasted approximately 0.5 billion years. In the case of Earth, it is well established that the so-called Late Heavy Bombardment ended around 3.8 billion years ago.

It is already known that:

1. The emergence of life on Earth was preceded by a stage of chemical evolution of matter outside the Earth.
2. The heredity of self-reproducing systems that characterize life is carried out through a “genetic” code.
3. The amino acids in proteins of living organisms exhibit molecular asymmetry (chirality), meaning that proteins are composed exclusively of “left-handed” amino acids.
4. The spontaneous emergence of such chiral asymmetry under terrestrial conditions is unlikely; it is assumed that these amino acids may have formed outside the Earth.

Below are five essential steps required for the formation of prebiotic molecules:

1. **Formation of simple molecules** — e.g., molecular hydrogen (H_2).
2. **Formation of dust grains and their icy mantles** — with sizes of about 0.01–0.3 μm .
3. **Molecular complexification** — formation of more complex organic molecules.
4. **Formation of protocells** — isolated systems enabled by membrane formation.
5. **Chiral selection (chiralization)** — the dominance of “left-handed” amino acids in terrestrial life.

Step 1. Formation of Molecules

The first and most evident step toward the origin of life is the synthesis of molecules, starting from the simplest one—molecular hydrogen (H_2).

Let us compare two timescales: molecule formation and molecule destruction. Molecule formation occurs on the surfaces of dust grains in regions of molecular clouds shielded from ultraviolet (UV) radiation.

The estimated timescale for this process is as follows:

$$t(H_2)(\text{formation}) = \frac{1.5 \cdot 10^9}{n} \text{ yr},$$

If the density of the interstellar molecular cloud is $n \geq 10^6 \text{ cm}^{-3}$, then

$$t(H_2) < 1500 \text{ yr}$$

Approximately this much time is also required for H₂ molecules to be destroyed in regions unshielded from ultraviolet (UV) radiation. The destruction timescale is estimated as:

$$t(H_2) \text{ (destruction)} = \frac{1}{k(\text{UV})} = \frac{1}{10^{-11} - 10^{-9}} \text{ s} \approx 33 - 3300 \text{ yr}$$

Step 2. Dust

Dust is essential in the interstellar medium, including as a substrate for further molecular complexification. In the early Universe, due to the scarcity of heavy elements, dust had not yet formed, and molecules (including H₂) were produced in the gas phase, which was not very efficient.

We link the emergence of life to the last 6–7 billion years, when dust was already present in near-modern amounts. Dust forms:

- In the remnants of supernovae (mainly silicates: SiO and similar oxides)
- In the cold stellar winds of red giants and AGB-type stars (mainly graphite)

In these environments, the vapor pressure of saturated gases was high enough for dust to condense from the gas phase.

Initially, grain cores form with sizes of ~0.01 μm, upon which, under favorable conditions, icy mantles can accumulate up to ~0.1 μm thick. Icy mantles consist of condensates of the most abundant molecules such as H₂O, CO, CO₂, CH₄, NH₃, HAC, CH₃OH, etc.

The timescale for the growth of icy mantles is estimated as:

$$t = \frac{3.0 \cdot 10^9}{n} \text{ yr}$$

If $n \geq 10^6 \text{ cm}^{-3}$, then $t < 3000 \text{ yr}$ (T = 10–20 K).

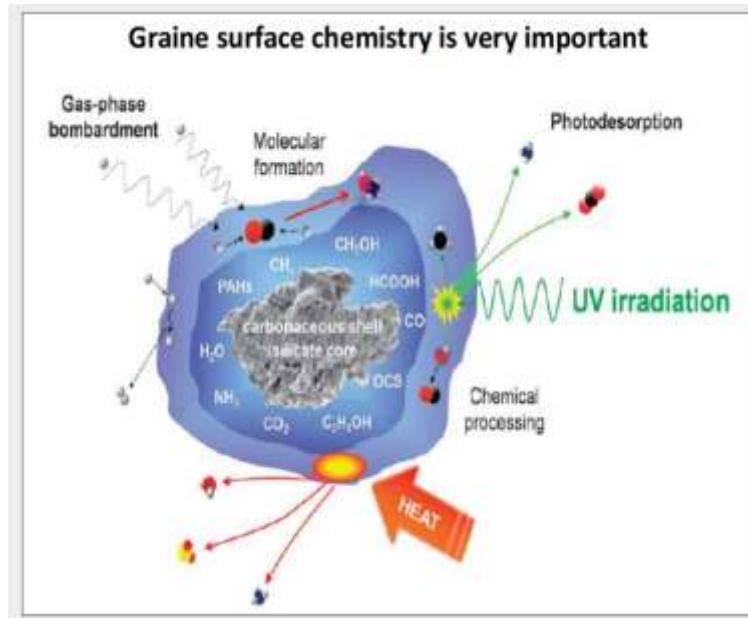
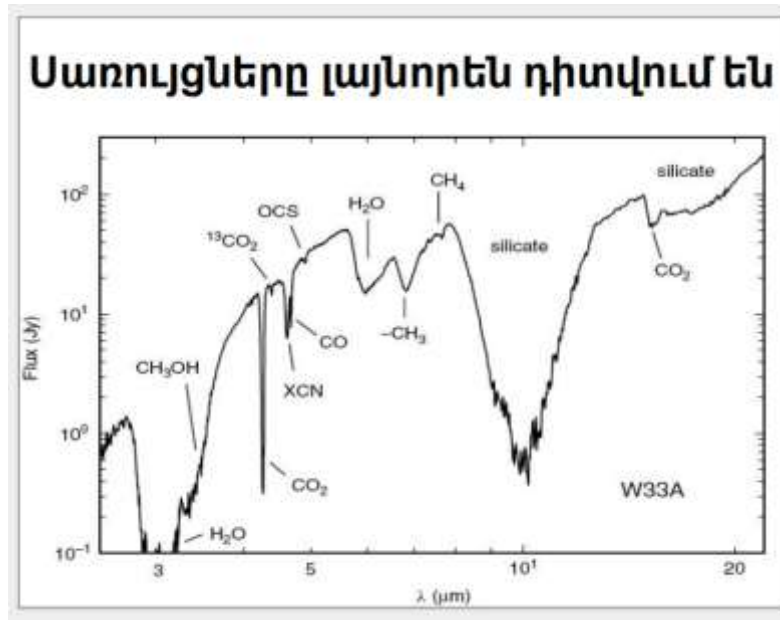


Fig. Schematic of a dust grain core and its icy mantle.

It should be emphasized that ices are observed in star-forming regions, as shown in the corresponding figure.

Step 3. Molecular Complexification

Molecular complexification, i.e., the synthesis of more complex organic compounds, is most effective in the solid phase, unlike the gas phase, which requires high temperatures and pressures. Such conditions would contradict Step 5, which involves the formation of chirality in life.



In the solid phase, one can provide examples of the necessary chemical reactions that occur at the low temperatures characteristic of molecular clouds.

This concerns the possibility of **radiation-driven chemical polymerization in ices**, which has been experimentally verified in two cases:

1. Using electromagnetic irradiation with photons of 6–13.6 eV energy
2. Using high-energy particles in the range 1 MeV–1 GeV, such as protons and α -particles

Interestingly, in molecular clouds, these cosmic particles in the specified energy range should be considered **primary**, because interactions with interstellar molecular hydrogen also contribute to the effect of 6–13.6 eV ultraviolet (UV) photon irradiation. Of course, the irradiation itself also plays a role from the other side.

Known estimates indicate that this is possible under such conditions, both in terms of the presence of radiation and the existence of ices.

Referring back to the decisive experiments that confirmed molecular complexification in interstellar cloud conditions, it should be noted that, as of early 2025, a large number of experiments have been conducted. Here we refer to only two publications:

- Kaiser & Roesler, 1990–2000
- Dworkin et al., 2004

The experiments irradiated pure ices and their mixtures at 5–10 K, including H₂O, CO, CO₂, NH₃, CH₄, CH₃OH, which are abundant in interstellar clouds.

The irradiation sources were various accelerators, where beams of accelerated particles (mainly 5–10 MeV protons, α -particles, and electrons) were used to irradiate the above ices. In the early stages of the experiments, ⁶⁰Co (γ -gun, gamma-ray source) was also used.

For ultraviolet (UV) irradiation, various hydrogen lamps (10–12 eV energy) were applied. As a result, amino acids, complex hydrocarbons, and other organic compounds were detected.

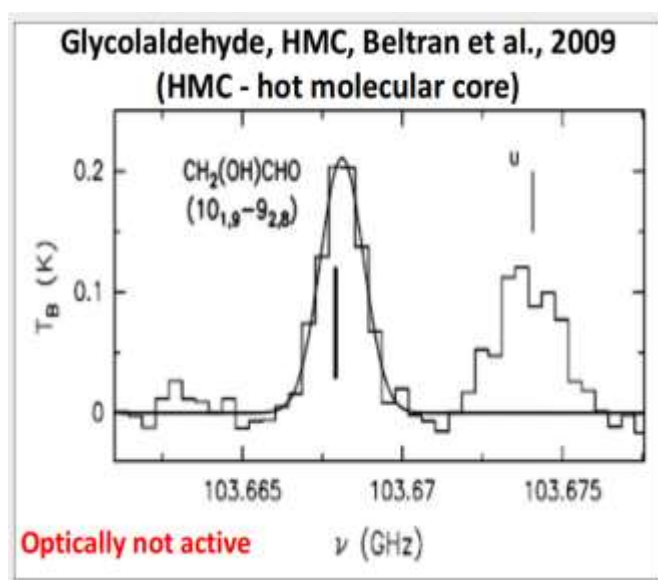


Fig. A representative of simple sugars, detected in star-forming regions.

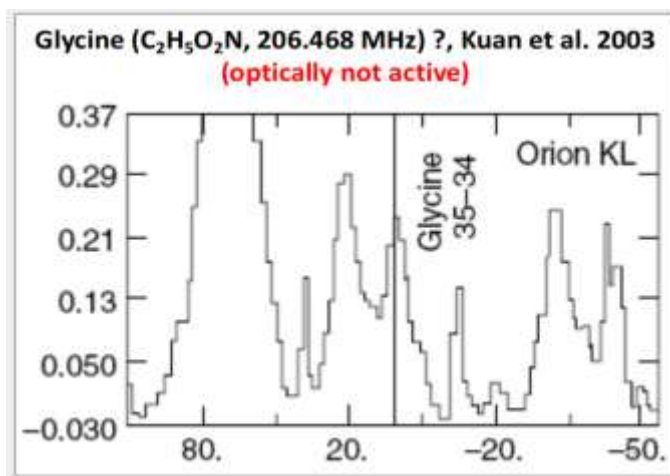


Fig. Probable identification of glycine in the Orion molecular cloud.

In addition to interstellar clouds, complex molecules have also been found in meteorites that have fallen to Earth since its formation. As noted earlier, the flux of meteorites was strong during the first half-billion years, until about 3.8 billion years ago, then it almost ceased, and now only episodic impacts reach the Earth's surface.

Analysis of the composition of meteorites (not all, only the so-called carbonaceous type) revealed the following elements, presented in the table.

Carbon containing species in meteorites – aa with ee !		
Compound class		Concentration (ppm)
Amino acids/CM meteorites	Optically active	17–60
Amino acids/CI meteorites		~5 ^a
Aliphatic hydrocarbons		>35
Aromatic hydrocarbons		3319 ^b
Fullerenes		>100 ^c
Carboxylic acids		>300
Hydrocarboxylic acids		15
Dicarboxylic acids and Hydroxydicarboxylic acids		14
Purines and Pyrimidines		1.3
Basic N-heterocycles		7
Amines		8
Amides linear		>70
Amides cyclic		>2 ^d
Alcohols		11
Aldehydes and Ketones		27
Sulphonic acids		68
Phosphonic acids		2

As we can see, amino acids, various hydrocarbons, and other complex molecules are present in these formations, and importantly, they are optically active. This is not contamination, since the concentration does not decrease from the surface toward the interior of the sample.

Before moving to the next step, let us briefly discuss the possible circulation of organic material in the Galaxy, according to **Kwok (2000)**.



Fig. Circulation of organic material in the Galaxy

Diffuse interstellar clouds transform into molecular clouds in the Galactic plane, within so-called gravitational potential wells where interstellar matter can condense. Organic compounds form in molecular clouds, most efficiently on the surfaces of dust grains, and undergo further complexification. In star-forming regions, this material reaches its highest level of complexity, acquiring the property of chirality, which will be discussed in detail in the next step.

The lower figure shows examples of detections of complex molecules, namely the presence of PAHs in cold stellar winds and C_{60} fullerene in diffuse clouds.

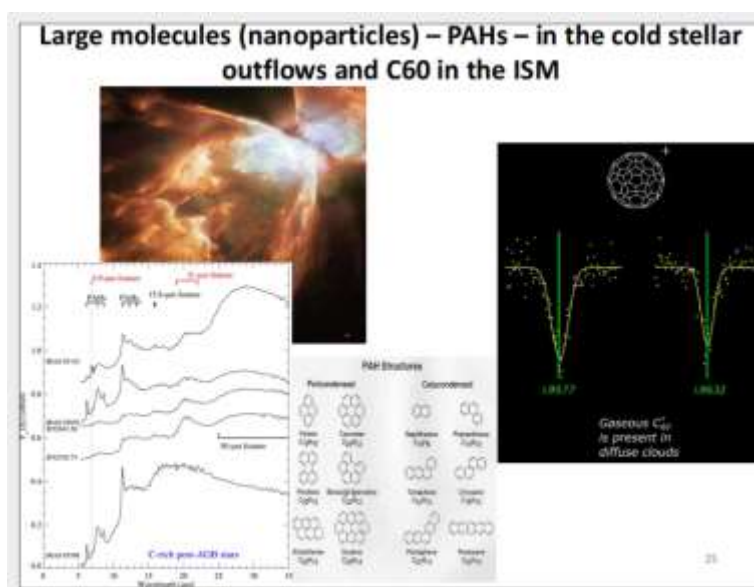


Fig. Examples of detections of polycyclic aromatic hydrocarbons (PAHs) and fullerene

Step 4. “Isolation” from the environment

Under laboratory conditions, research on protocell formation is actively ongoing, using chemically active so-called “droplets” (Fig.).

These are not yet true protocells, since they cannot divide independently. However, in many respects they are close to protocells, and experimental studies are continuing.

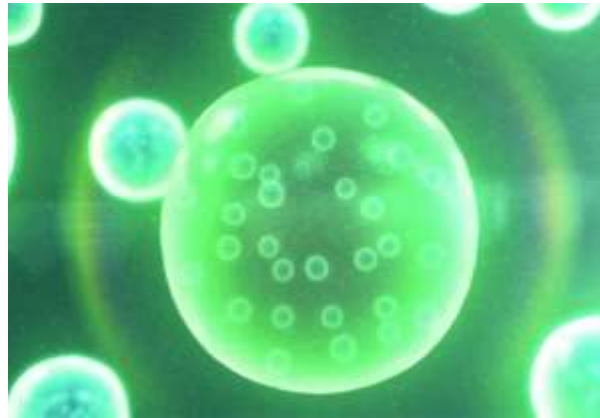


Fig. Chemically active “droplets” as a model of protocells on the early Earth.

Under molecular cloud conditions, an effective mechanism for the formation of chiral molecules could be **selective photochemistry**, that is, the irradiation of the aforementioned ices with 6–13.6 eV circularly polarized light (CPL).

Such an experiment has been performed, and the resulting amino acids were found to be chiral (**Nuevo et al., 2006**).

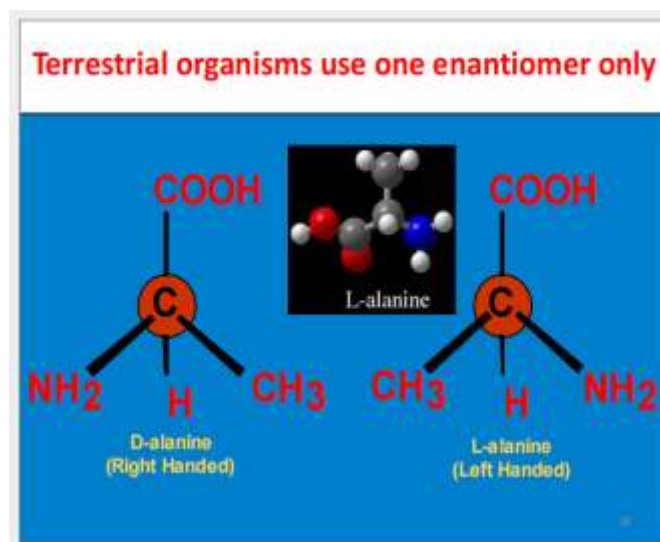


Fig. Proteins in Earth's living organisms contain only one specific type of chiral molecules

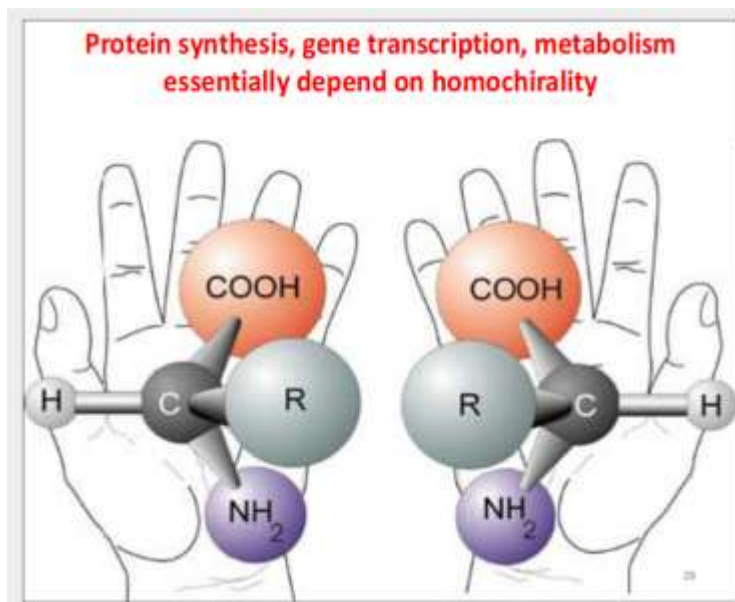


Fig. The same molecules, with one being the mirror image of the other

It should be emphasized that the **Miller–Urey experiments**, which are described in all biology textbooks, demonstrate the following: a mixture of methane, ammonia, water, and hydrogen, when exposed to an energy source such as electric sparks (or natural lightning), produces amino acids, hydrocarbons, and other compounds after a few hours in the experimental flask.

However, such experiments have very little relevance to the actual origin of life on Earth. Most importantly, the amino acids produced this way are **racemic**, meaning a **50:50 mixture of left- and right-handed forms**, which is normal for natural, non-biochemical reactions. Astrophysicists note the absence of a source of asymmetric energy.

Another critical factor is that the early Earth's atmosphere, immediately after formation (4.5–4 billion years ago), was **neutral** ($\text{CO}-\text{CO}_2$, N_2), with hydrogen, methane, and oxygen largely absent. Therefore, carbon compounds containing, for example, 15 carbon atoms could not form via the known **Fischer–Tropsch reactions**. In essence, polymerization and polycondensation reactions could not naturally produce complex molecules.

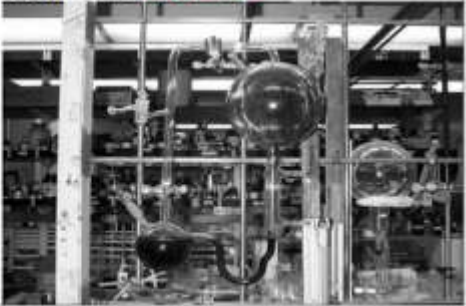
Another important point is that the early Earth's atmosphere, immediately after formation (4.5–4 billion years ago), was **neutral** ($\text{CO}-\text{CO}_2$, N_2), with hydrogen, methane, and oxygen largely absent. Therefore, carbon compounds containing 15 carbon atoms could not form via the known **Fischer–Tropsch reactions**.

In essence, polymerization and polycondensation reactions could not naturally produce complex molecules.

Are Miller-type experiments adequate ? No !

1. Terrestrial primitive atmosphere was not reduced (no H_2 , CH_4 → **no polymerization/condensation**)
2. Produced aminoacids are **racemic**.

CH_4
 NH_3
 H_2O
 H_2
+
Energy
source



Thus, we have outlined **five steps** necessary for the formation of prebiotic molecules outside Earth, and subsequently, their delivery to Earth. The subsequent developments, up to the appearance of self-replicating entities, remain unclear to science.

Let us clarify where such biomolecules, formed in star-forming regions or, with some reservations, in protoplanetary disks, come from and deposit on Earth. On a planet such as Earth, this would not have been possible due to the absence of an asymmetric factor. This question remains open and requires serious analysis.

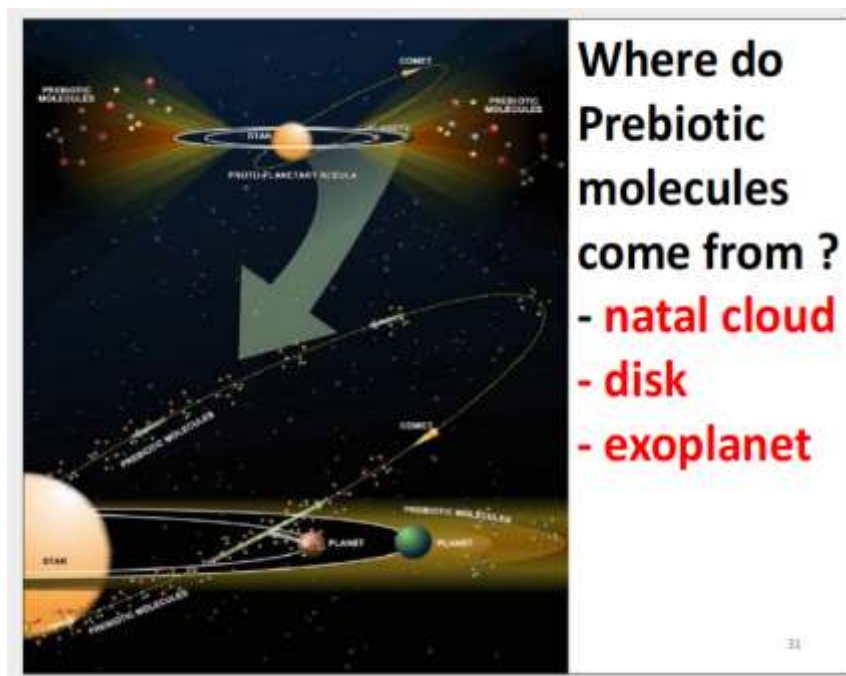


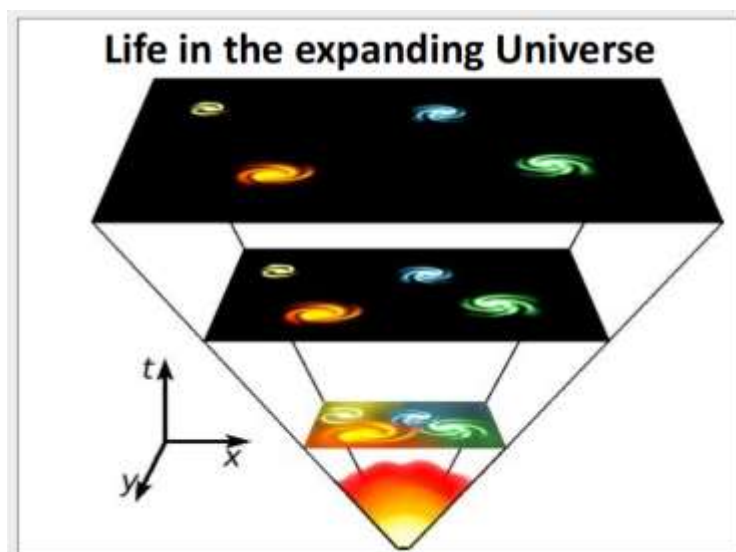
Fig. Origin of prebiotic molecules on Earth (or other planets).

In short, this concerns **the origin and survival of life in an expanding Universe**. Observations show that energetic events in the Universe diminish over time.

It is clear that in an expanding Universe, radiation decreases due to spreading over larger volumes, and, as noted, the intensity of sources also declines. A quantitative measure can be established using the **time evolution of the radiation dose**.

The radiation dose is defined as the absorbed fraction of radiation energy, which requires knowledge of the radiation flux, exposure time, and the interaction cross-section with the molecule. Calculations indicate that during the first half of the Universe's age (6–7 billion years), radiation exceeded the threshold dose for molecule carbonization, whereas in the second half (7–13.5 billion years) it was lower.

In this respect, disregarding other factors, it can be said that only during the last **7–13.5 billion years** has the Universe been favorable for the survival of complex organic compounds.



Preliminary results of radiation dose calculations

The doses were calculated in molecular clouds within star-forming regions for radiation durations of 1–10 million years.

1. Radiation fluxes (gamma-ray—GR and cosmic rays—CR) are known from star formation rates.
2. The evolution of heavy elements was not considered; thus, the calculated doses can be regarded as a lower bound.

Calculation results:

- 13.8–7 billion years ago: doses **2000–100000 eV/amu**
- 7–5 billion years ago: doses **1–50 eV/amu**

The carbonization dose is approximately **2000 eV/amu** (PAH dehydrogenation, C_{60} amorphization).

From the perspective of complex organic molecule formation and survival, the Universe has been favorable for the existence of prebiotic molecules **only during the last 7 billion years**, making life on Earth among the earliest.

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