From dying stars to the proto-Solar nebula -the chemical evolution of interstellar matter

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Abstract

An overview of the circulation of interstellar matter is presented. Many processes contribute towards increased chemical complexity in the interstellar gas, but an essential prerequisite is the existence of dust grains. These particles are effectively formed in the atmospheres of evolved stars, and distributed into the surrounding space when the dying star becomes a 'planetary nebula'. Even though the formation of most chemical species detected in the interstellar space (about 120) can be understood in terms of gas-phase reactions, dust grains provide catalytic surfaces for some of the most important reactions. Gravitational contraction of clouds and chemical evolution within them lead to a situation in which heavy molecules start to freeze onto grain surfaces. The molecular ices formed in this way can be exposed to UV radiation when stars are born inside the cloud, and their photolysis can initiate the production of biogenetic molecules found (e.g.) in meteorites. Prebiotic molecules may therefore be present in very dense discs surrounding protostars. When the newly born star bursts through, the outer parts of the protostellar disc, the so-called 'debris disc' can still survive and form a reservoir, which later on can replenish planetary surfaces with complex molecules carried by interplanetary dust particles originated in comets.

1 Red giants - dust factories

When the fusion reactions converting hydrogen to helium cease in the centre of a low- to intermediate mass star like our Sun, the 'hydrogen burning' proceeds in a shell moving outward. In this phase the outer parts of the star expand greatly and cool down. The star becomes a red giant. The competing heating and cooling processes give rise to periodic changes of the radius of the star and thereby to its surface temperature and brightness. A prototypical red giant, the first known variable star Mira, "the Wonderful", was discovered in the constellation of Cetus in 1596.

The ionized gas in the expanding shell of a red giant can recombine into atoms, which in turn can form simple molecules, such as carbon monoxide (CO), silicon monoxide (SiO) and acetylene (C_2H_2), which are stable at high temperatures. In the conditions of expanding circumstellar shells free atoms and light molecules can further condense into dust particles (or smoke). Depending on atomic abundance ratio of oxygen, O, and carbon, C, the dust grains can be either silicates (minerals building upon SiO_4 chains) or various forms of carbon or hydrocarbons, e.g. graphitic carbon and aromatic hydrocarbons formed from C_2H_2 chains.

The star becomes invisible as the dusty envelope grows thicker. The physical conditions and the kinematics of the envelope can be studied with the aid of infared and radio spectroscopy.

The expansion driven by radiation pressure gets faster by time. Eventually the dust layer becomes transparent again, and the inner gas shell excited by the radiation from the central star is seen as a shell-like structure, a so-called 'planetary nebula'. Interstellar ultraviolet radiation field dissociates molecules in the outer parts of the shell. Also dust grains and various carbonaceous particles are subject to destructive processes, but part of them survive in the hard conditions, and together with atoms and ions ejected from the dying star these become a part of the diffuse interstellar medium. Most of the 'stardust' originates in low- to intermediate mass stars. On the other hand, supernova explosions enrich the interstellar medium by iron (^{56}Fe) and heavier elements, and are important for the dynamics of interstellar clouds.

2 Chemistry between stars

Various dynamical processes - spiral density waves in the Galaxy, supernova explosions, winds and radiation from massive stars - sweep interstellar matter into condensations which can be seen as obscuring, sometimes glowing clouds in the sky. The obscuration is caused by absorption and scattering
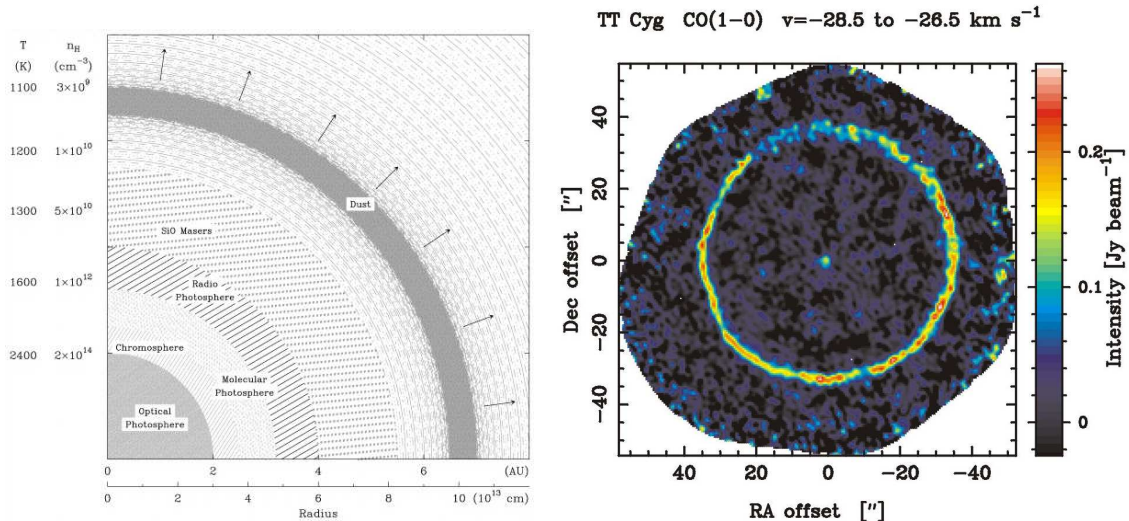
Figure 1: **Left:** Schematic presentation of the extended atmosphere of a Mira-type variable star from Reid & Menten ([10]). The locations of various phenomena and the radial distributions of the gas kinetic temperature and number density are shown. Dust grains form at the kinetic temperature ~ 1000 K. The particle density in this region is a few times 10^6 cm^{-3}. The dust shell is pushed away from the star by the radiation pressure. **Right:** Thin molecular shell around the variable carbon star TT Cygni (Olofsson et al. [5]). An interferometric map of the CO $J = 1 - 0$ line emission at $\lambda = 2.7$ mm. The radio photosphere of the star can be seen as a point source in the centre of the image. The shell expanding at the velocity 12.6 km/s has a radius of 20000 AU and a thickness of 1000 AU.

of light by dust particles. Even though dust constitutes only about one percent of a cloud's mass, its presence has very important implications to the interstellar chemistry. First, the dust shields the interiors of clouds from radiation and thereby contributes to the survival of molecules. Second, the most common molecule, H_2, is believed to form primarily, and very efficiently on the surfaces of dust grains in interstellar clouds.

Interstellar clouds with particle densities above 1000 cm^{-3} or so are predominanly composed of H_2 and, consequently, called 'molecular clouds'. These clouds are characterized by low densities and temperatures (10-20 K), low degrees of fractional ionization ($10^{-8} - 10^{-7}$), weak magnetic fields (a few tens of μG), and relatively large turbulent velocity dispersions, typically on the order of 1 km/s, which is probably related to their formation through turbulent fragmentation. The ionization is believed to be sustained by cosmic rays (mostly energetic protons originating in supernova explosions).

The formation of more complex molecules in obscured clouds begins with the cosmic ray ionization of the hydrogen molecule ($H_2 \rightarrow H_2^+$) followed by the reaction

$$H_2^+ + H_2 \rightarrow H_3^+ + H .\qquad (1)$$

The H_3^+ ion can then react with O and C atoms to form simple molecular ions and molecules containing H,O, and C, e.g., OH, H_2O, HCO$^+$ and CO. Reactions between positive ions and neutrals, and recombination reactions between ions and electrons occur faster than neutral-neutral reactions and are thus important in the rarefied gas in the interestellar space. Nitrogen chemistry is, however, initiated by relatively slow neutral reactions, and the abundances of such compounds as NH_3, N_2H^+ and HCN are believed to build up at later stages than for example those of carbon chains and water.

Molecular hydrogen is by far the most abundant constituent of molecular clouds. In typical interstellar conditions H_2 remains in its ground rotational and vibrational states, and is unobservable by emission. In contrast, the lowest rotational levels of the most common diatomic molecule, CO, are easily excited in molecular clouds. This molecule and its isotopomers, such as ^{13}CO and C^{18}O have been used extensively for the mapping of interstellar clouds. Other common molecules used for spectroscopic studies are, e.g., OH, NH_3, CS, H_2CO, and N_2H^+. The largest molecule detected with confidence in interstellar clouds contains 13 atoms (HC$_{11}$N). The number of different chemical species detected so far exceeds 120 (see e.g. www.cv.nrao.edu/~awootten/allmols.html).

While observers have been mapping distributions of various molecules, theoretical chemists have developed extensive models in order to explain the observed abundances and their variations in interestellar clouds. The models have developed from simplistic equilibrium chemistry models to time dependent ones. At present the models are capable to account for both gas-phase reactions and
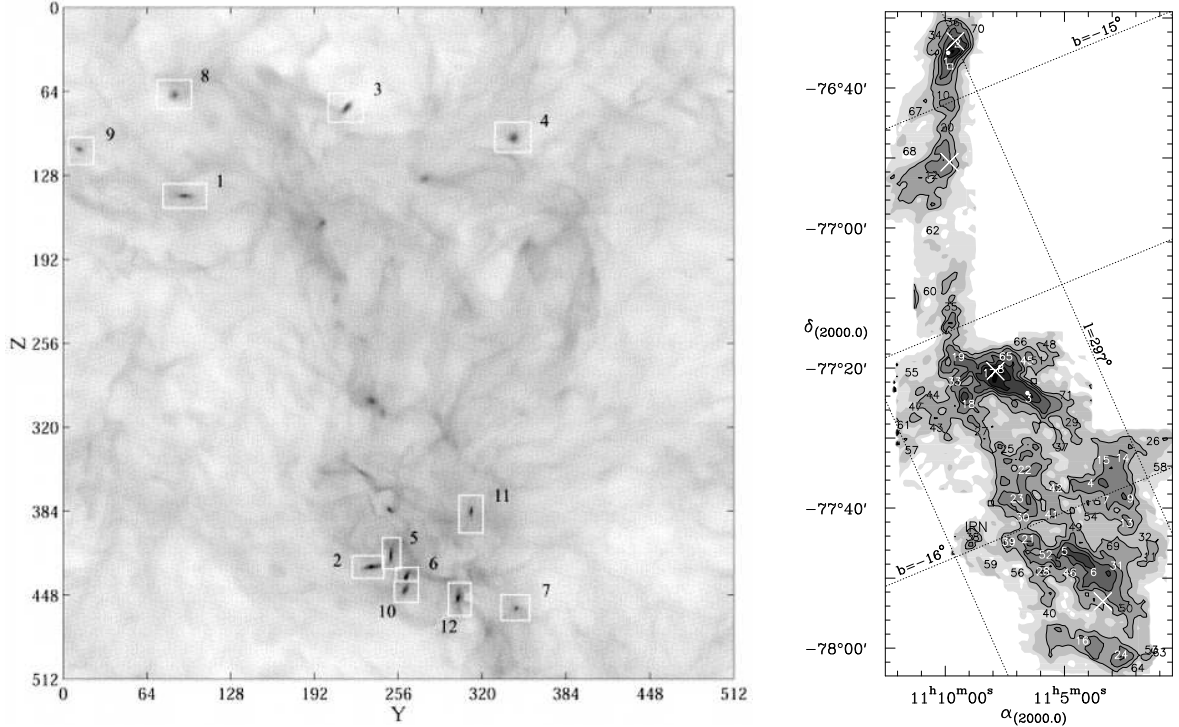
Figure 2: **Left:** Gas column density map resulting from MHD simulations of molecular cloud fragmentation by Li et al. ([8]). Several dense cores (numbered), i.e. potential sites of star formation can be identified in the map. **Right:** Column density distribution of dense gas as traced by the $C^{18}O$ molecule in the Chamaeleon I cloud (Haikala et al. [3]). The locations of dense cores identified by an automatic routine are indicated.

grain-surface reactions plus the dynamical evolution of the cloud (e.g. Aikawa et al. [2]; Aikawa et al. [1]). Testing these models is a great challenge for observational astrophysics.

The interpretation of molecular line maps is not always straightforward. Chemical abundances are time-dependend. Furthermore, molecules freeze onto grain surfaces, and become heavily depleted in cloud centres. Bolometer receivers sensitive at the far-infrared and submillimetre wavelengths where the thermal emission from dust peaks have turned out to be very useful instruments for revealing the structures of molecular clouds. A combination of molecular line and dust continuum observations is often the best way to investigate the densest part of a molecular cloud.

3 Dense cores

Molecular clouds are supported against global gravitational collapse by their supersonic turbulent motions, and possibly by the magnetic field pressure. On the other hand, turbulent shocks give rise to local density enhancements, "clumps", which can become gravitationally bound and collapse to form stars. Interstellar turbulence is likely to be driven on large scale by supernova explosions and massive stellar winds and maintained by magnetic fields. Recent magnetohydrodynamic (MHD) simulations of turbulence-driven fragmentation have fairly well managed to reproduce the morphological features of interstellar clouds, but much work is still needed before the relations between turbulence, clump characteristics, and the mass distribution of stars formed in them can be understood (see e.g. Klessen [6], Li et al. [8]).

The collapse of the interior parts of a core is possible through cooling by molecular lines and thermal dust emission. These forms of emission provide also means of studying the physical conditions and composition of obscured, cold nuclei of dense cores. In these regions most of the heavy molecules are likely to be frozen on grains. Some nitrogen molecules, e.g. NH_3 and N_2H^+, seem to be able to withstand depletion longer than molecules containing carbon or oxygen, but in the core centres also they should freeze out. Compounds remaining in the gas phase are the hydrogen molecules H_2, H_3^+ and their deuterated substitutes. The deuterated species HD, H_2D^+, and D_2H^+ have small dipole moments, and thus rotational spectra. The ground-state rotational lines of H_2D^+ and D_2H^+ have been recently detected in dense, cool interstellar gas at radio wavelengths(Stark et al.[12]; Vastel et al. [14]), and these lines can become important tracers of the quiet depths of molecular clouds.
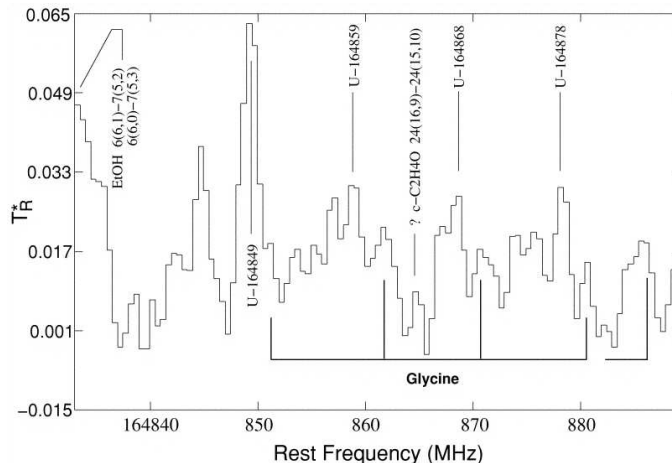
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Figure 3: One of the frequency bands used by Kuan et al. ([7]) in search for the simplest amino acid, glycine (NH_2CH_2COOH). The group reported the first detection of glycine in interstellar space towards the massive, warm molecular cloud cores in Sgr B2, Orion, and W51. Altogether 27 lines were detected in 19 frequency bands. The spectrum towards Orion shown here demonstrates the difficulty of unequivocal identification of complex molecules. The weak lines of glycine are distributed over a wide range of frequencies, and the source of emission shows a multitude of confusing lines of other, more abundant molecules. The reality of the detection has been disputed by Snyder et al. ([11])

As the gas-phase chemistry becomes rather limited, icy mantles covering grains grow thicker, and reactions in their mantles produce saturated molecules by hydrogenation, thanks to the high mobility of H atoms. Water (H_2O), carbon monixide (CO), methane (CH_4), and ammonia (NH_3) are probably the main constituents of icy mantles. Other molecules amply present in these mantles are methanol (CH_3OH), formic acid (HCOOH), formaldehyde (H_2CO), and carbon dioxide (CO_2).

Very complex organic molecules may form in icy mantles when they are exposed to ultraviolet radiation. According to laboratory photolysis experiments these may include polymers, hydrocarbons, hydroxy acids and amides, and amino acids.

The identification of complex prebiotic molecules in interstellar space is difficult. In principle this can be done using infrared spectroscopy of ices or gaseous molecules (vibrational lines) or radio spectroscopy of gaseous molecules (rotational lines). The vibrational spectra consist of streching and bending lines of various bonds (e.g. C-H) which are difficult to attribute to any specific molecule. On the other hand, rotational spectroscopy is hampered by the fact that these molecules are released into the gas phase only for a short time when the material is heated by radiation or winds from a nearby star.

4   Protostars

The collapse of a molecular core probably proceeds inside-out, and leads to the formation of an isothermal spherical nucleus, i.e. a protostar. The central mass is initially on the order of 10^{-3} solar masses, i.e. that of Jupiter, and increases by three orders of magnitude over a time scale of $10^4 - 10^6$ years as the surrounding material accretes on it. The conservation of the angular momentum of the infalling material results in a rotating disc in the equatorial plane of the protostar. Disc winds and jets emanating close to the protostellar surface aided by magnetic fields drive bipolar outflows, which carry away the 'extra' angular momentum and enables further contraction. The picture is certainly very simplistic in view of the fact that most stars are binaries or multiple stars. Single stars provide, however, the most stable conditions for the development of life, and it is particularly important to understand details of their formation. For recent MHD simulation of early phases of stellar evolution see e.g. Tomisaka ([13]) and Machida et al. ([4]).

A circumstellar, flaring disc extending typically to about 1000 AU from the star is left over after the main accretion phase of a low-mass star like our Sun. Radial temperature and density gradients in the disc cause also a chemical gradient. The warm inner part is characterized by equilibrium chemistry, whereas ion-molecule reactions are dominant in the cool outer parts. Small dust particles are almost completely destroyed within radii of about 10 AU from the central pre-main sequence star. Furthermore, the irradiation has a significant effect on the dust temperatures and the compositions of gas and icy mantles of grains up to distances of 100 AU. Like dense, star forming cores, the outer
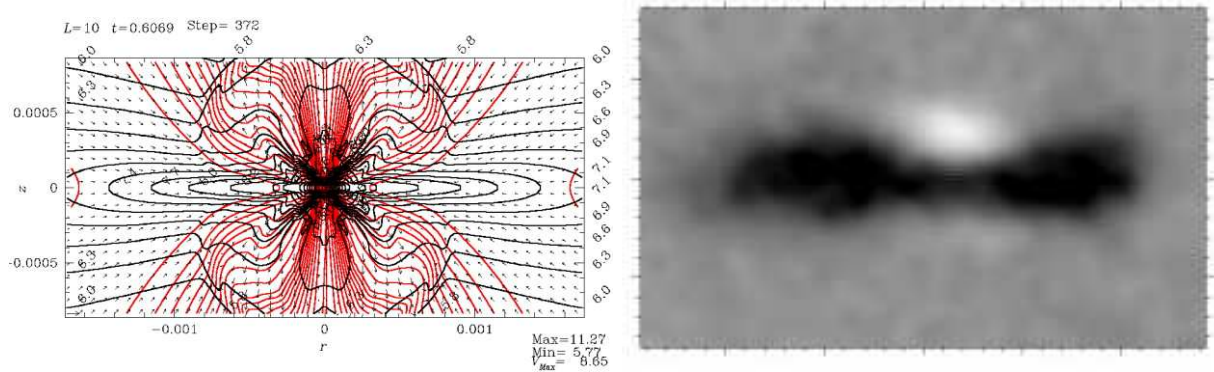
Figure 4: **Left:** An early stage of protostellar evolution as modelled by Tomisaka ([13]). The solid lines represent isodensity contours, the dotted lines magnetic fields, and the arrows velocity vectors. At this phase an outflow begins to emanate from the inner disc at the same time as matter is accreting through the outer disc. **Right:** A near-infared image of the edge-on sihouette disc Orion 114-426 seen against the Orion Nebula. The image is taken using the Hubble Space Telescope by McCaughrean et al. ([9]). The diameter of the disc is about 1000 AU. The central protostar is betrayed by two polar reflection nebulosities. This object represents a much later phase than the model of Tomisaka.

parts of protoplanetary discs are likely to provide favourable conditions for the production of prebiotic molecules.

The planetary materials in our Solar system are heavily processed. On the other hand, information on the composition of the proto-Solar nebula can still be obtained from meteors and comets. Some meteoritic materials (e.g. SiC grains and graphite) carry memory of their birth place, and many of their organic molecules, including dozens of amino acids not found in the living organisms on the Earth, are almost certainly of interstellar origin. Molecular abundance ratios determined in comets (using radio spectroscopic observations) correspond to those in interstellar ices.

Besides the fact that the Earth has been bombarded by asteroids, especially in its early history, it is constantly invaded by interplanetary dust originating in comets and asteroids, which contain nearly unprocessed material from the times of the proto-Solar nebula. The present estimation is that about 300 million tons of 'space dust' sprinkle down on the Earth each year.

5   Conclusions

Dust grains produced in the envelopes of dying stars are necessary for the formation of the most common molecule, H_2, but they also provide a substrate for increasing molecular complexity in interstellar space. Chemistry between stars is characterized by gas-phase ion-molecule reactions and molecular abundances far from equilibrium chemistry. In very dense parts of molecular clouds, i.e., the birthplaces of stars, almost all heavy molecules freeze onto dust grains. Saturated molecules build up on grain surfaces via hydrogenation reactions. Photolysis of icy mantles by the UV radiation from a nearby or an embedded star can lead to the formation of very complex organic molecules, e.g. amino acids. Stars and planets form from interstellar gas and dust, but complex molecules cannot survive this process and become directly progenitive to life on planets. The outer parts of the protoplanetary disc may, however, become a reservoir of interstellar ices. These ices can be transported to the inner parts of the planetary system by comets, and enter planetary surfaces both by violent collisions and in the form of interplanetary dust particles floating quietly down through the atmosphere.

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6   The most important concepts

red giant: evolved star with the nuclear reactions occurring in a 'burning shell' - *punainen jättiläinen*

planetary nebula: emission nebula with a planet-like appearance, made of the ejected envelope of a red giant - *planetaarinen sumu*

molecular cloud - interstellar cloud with most of its hydrogen in molecular form, H_2 - *molekyylipilvi*

dense core: cool and dense condensation within a molecular cloud, a potential birth place of stars - *tiheä ydin*

protostar: an early stage of stellar evolution before nuclear reactions have started - *prototähti*

accretion disc: gravitationally bound differentially rotating disc through which matter spirals into the central object - *kertymäkiekko*

protoplanetary disc: debris disc remaining in the equatorial plane of a protostellar system from which planets can from - *esiplanetaarinen kiekko*

prebiotic molecule: a molecule containing biochemical elements from which life can originate - *esielollinen yhdiste*