FROM MOLECULAR CLOUDS TO THE ORIGIN OF LIFE

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1 Abstract

We review the current knowledge about organic molecules and solids in the interstellar medium and solar system objects and investigate their possible role in the origin of life. Astronomical observations with ground and space-based observatories have revealed more than 120 organic molecules which reside in the interstellar medium and in circumstellar shells. We summarize recent searches for the amino acid glycine and other large organic molecules in dense molecular clouds and monitor their evolution until their incorporation into solar system material. We discuss the current knowledge on the chemistry of protoplanetary disks which provides important information on the conditions of the solar nebula. The fate of organic molecules during solar system formation is strongly tied to the local environmental conditions and the radial distance from the protosun. In the inner solar nebula organic molecules were partly destroyed and chemically processed but organics may have been integrated into solar system bodies in rather pristine form in regions of low temperature and pressure in the outer solar system. Comets and meteorites being an assembly of solar and presolar material encode therefore crucial information on their origin. They can be used as a tracer for processes which were predominant in the protosolar nebula. We also describe the role of comets and meteorites in the transport of organic matter to planets in the early solar system. Finally, we discuss the likelihood of the emergence of life on Earth being due to prebiotic molecules of meteoritic origin.

2 Introduction

In our Milky Way and in external galaxies, the space between the stars is filled with an interstellar medium (ISM) consisting of gas and dust. The ISM can be divided in various different components with very different physical parameters, ranging from a very hot (10^6 K), dilute ($< 10^{-2}$ particles cm^{-3}) component heated by supernova explosions, which fills more than half of its volume, to molecular clouds with temperatures from 10 to 100 K and molecular hydrogen (H_2) densities from a few hundred to 10^8 cm^{-3}, which make up less than 1% of the ISM's volume. Approximately 1% of its mass is contained in microscopic (micron-sized) interstellar dust.

While accounting for only a small fraction ($\sim 1\%$) of the Galaxy's mass, the ISM is nevertheless an important part of the Galactic ecosystem. Gravitational collapse of dense interstellar clouds leads to the formation of new stars, which produce heavier elements in their interiors by nucleosynthesis. The main reaction in stellar interiors is the nuclear fusion of H into He. In a later stage of stellar evolution C, N and O are formed. Further nucleosynthesis occurs in massive stars leading to elements as heavy as iron. At the end of their lifetime, which is mainly determined by their initial mass, stars return material to the interstellar environment by mass outflows, forming expanding shells and envelopes, as well as by violent explosions. Thus, the ISM represents an environment in which atoms, molecules, and solid matter undergo strong evolution and recycling.

Observations at radio, millimeter, sub-millimeter, and infrared wavelengths have led to the discovery of well over a hundred different molecules in interstellar clouds and circumstellar shells (see Table 1). Many of these are organic species of considerable complexity, with $HC_{11}N$ (Bell et al. 1999) and diethyl ether [$(C_2H_5)_2O$] (Kuan et al. 1999) being the largest detected so far. In all cases, accurate line frequencies predicted by laboratory spectroscopy ensure an unambiguous identification. These molecules, which have abundance ratios relative to molecular hydrogen or less, and in many cases much less, than 10^{-4}, are important tracers of the physical conditions and chemistry of many different interstellar and circumstellar environments. Despite their

Number of Atoms										
2	3	4	5	6	7	8	9	10	11	12+
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N?	HC_9N	C_6H_6?
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN	$(CH_3)_2CO$		$HC_{11}N$
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH?	$(CH_3)_2O$	NH_2CH_2COOH?		PAHs
C_2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH			C_{60}^+?
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	$HCOCH_3$	H_2C_6	HC_7N			
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	NH_2CH_3		C_8H			
CN	HCO	CH_2D^+?	CH_4	CH_3SH	c-C_2H_4O					
CO	HCO^+	HCCN	HC_3N	HC_3NH^+						
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO						
CP	HOC^+	HNCO	HCOOH	NH_2CHO						
CSi	H_2O	HNCS	H_2CHN	C_5N						
HCl	H_2S	$HOCO^+$	H_2C_2O							
KCl	HNC	H_2CO	H_2NCN							
NH	HNO	H_2CN	HNC_3							
NO	MgCN	H_2CS	SiH_4							
NS	MgNC	H_3O^+	H_2COH^+							
NaCl	N_2H^+	NH_3								
OH	N_2O	SiC_3								
PN	NaCN	CH_3								
SO	OCS									
SO^+	SO_2									
SiN	c-SiC_2									
SiO	CO_2									
SiS	NH_2									
CS	H_3^+									
HF	H_2D^+									

Table 1: Interstellar and circumstellar molecules as compiled per October 2000. Observations indicate the presence of molecules larger than 12 atoms, such as polycyclic aromatic hydrocarbons (PAHs), fullerenes and others in the interstellar medium.

relatively low abundances, the variety and complexity of organic compounds currently detected in space indicates an active chemistry and ubiquitous distribution (for recent reviews see van Dishoeck & Blake 1998, Ehrenfreund & Charnley 2000). Extraterrestrial organics may have played a role in the origin and evolution of life (Oro 1961, Chyba et al. 1990, Bernstein et al. 1999).

The dense cold phases of the interstellar medium also host icy dust grains, whose molecular composition has recently been well constrained by observations from the Infrared Space Observatory (ISO) (Ehrenfreund & Schutte 2000, Gibb et al. 2000). These dust particles are important chemical catalysts and trigger molecular complexity in the interstellar gas and dust. In contrast to the case of gas phase molecules, the exact nature of interstellar solids cannot be unambiguously identified by astronomical observations, but can be constrained by laboratory techniques. Our knowledge of the carbonaceous solid state and gas phase inventories of molecular clouds has recently been reviewed by Ehrenfreund & Charnley (2000).

Numerous protoplanetary disks have been imaged with the Hubble Space Telescope (HST), indicating that the formation of extrasolar systems similar to our own solar system is a rather common process (McCaughrean & O'Dell 1996, Padgett et al. 1999). During star formation, interstellar molecules and dust become the building blocks for protostellar disks, from which planets, comets, asteroids, and other macroscopic bodies form (see Mannings et al. 2000).

Comets are agglomerates of frozen gases, ices, and rocky debris, and are likely to be the most primitive bodies in the solar system. Comets are formed in the outer solar system from remnant planetesimals that were not integrated into planets. Such comet nuclei were thrown into large high inclination orbits by perturbation of the major planets into the so-called Oort cloud at $\sim 50,000$ astronomical units (AU) from the sun. Comet nuclei that were formed near the plane of Neptune and beyond reside in the Edgewood-Kuiper belt (Jewitt et al 1998). When comets are perturbed and enter the solar system, solar radiation heats the icy surface and forms a gaseous cloud, the coma. During this sublimation process, “parent” volatiles are subsequently photolyzed and produce radicals and ions, the so-called “daughter” molecules. Space missions to comet Halley and recent astronomical observations of two bright comets, Hyakutake and Hale-Bopp, allowed astronomers to establish an inventory of cometary molecular species (Crovisier & Bockelée-Morvan 1999, Irvine et al 2000). Small bodies in the solar system, such as comets, asteroids, and their meteoritic fragments carry pristine material left over from the solar system formation process, thus sampling the molecular cloud material out of which the sun and planets formed.

3 The search for large organic molecules in dense clouds

To date, more than 120 molecules have been detected in the interstellar medium and the circumstellar environments of red giant stars, see Table 1. Most of these have rotational spectra at radio-, millimeter-, and submillimeter wavelengths, which can be efficiently observed with modern telescopes and detector equipment. Many interstellar molecules only exist in dense clouds, where they are sufficiently shielded from UV irradiation. In particular, a number of prebiotic species such as H_2CO, HCN, NH_3 have been identified.

3.1 The search for amino acids in the interstellar medium

For more than two decades, considerable effort has been devoted to various attempts of detecting the simplest amino acid, glycine (NH_2CH_2COOH) in interstellar molecular clouds. Glycine exists in a variety of conformations (e.g. Császár 1992) and the extensive laboratory microwave spectroscopy of conformers I and II (e.g. Lovas et al. 1995) allows meaningful astronomical searches. The very large partition function of a species as complex as glycine results in relatively weak lines which are difficult to detect in dense, warm molecular cloud cores due to confusion produced by a “forest” of weak lines from a large number of species that are also present in the region in question. Consequently, none of the searches conducted so far has resulted in an unambiguous detection; the best upper limits on the glycine-to-H_2 abundance ratio are of order 10^{-10} (Brown et al. 1979, Hollis et al. 1980, Snyder et al. 1983, 1995, Berulis et al. 1985, Combes et al. 1996, Snyder 1997, Ceccarelli et al. 2000, Charnley et al. 2001). As discussed by Snyder (1997), the use of high spatial resolution interferometric observations may bring some relief to the confusion problem as various classes of molecules (e.g. O-rich vs. N-rich species) have different spatial distributions and/or radial velocities (see also Mehringer et al. 1997).

The formation routes of amino acids in interstellar gas and dust are not yet established. Charnley (2000) proposed that protonated glycine could be formed in hot cores by reaction of protonated aminomethanol and HCOOH

$$NH_2CH_2OH_2^+ \;+\; HCOOH \;\longrightarrow\; NH_2CH_2COOH_2^+ \;+\; H_2O \tag{1}$$

Amino acids could also be formed in the solid phase by irradiation of interstellar grain mantles (Bernstein et al. 2001). However, amino acids are highly susceptible to UV photo-destruction, even under exposure to UV photons of relatively low energy (Ehrenfreund et al. 2001). Though low concentrations of amino acids may be detected by astronomical observations at radio wavelength in UV shielded environments, such as the hot cores and the inner cometary coma, all environments with an elevated UV flux should have merely traces of these compounds. This may explain the lack of detection of these compounds in space.

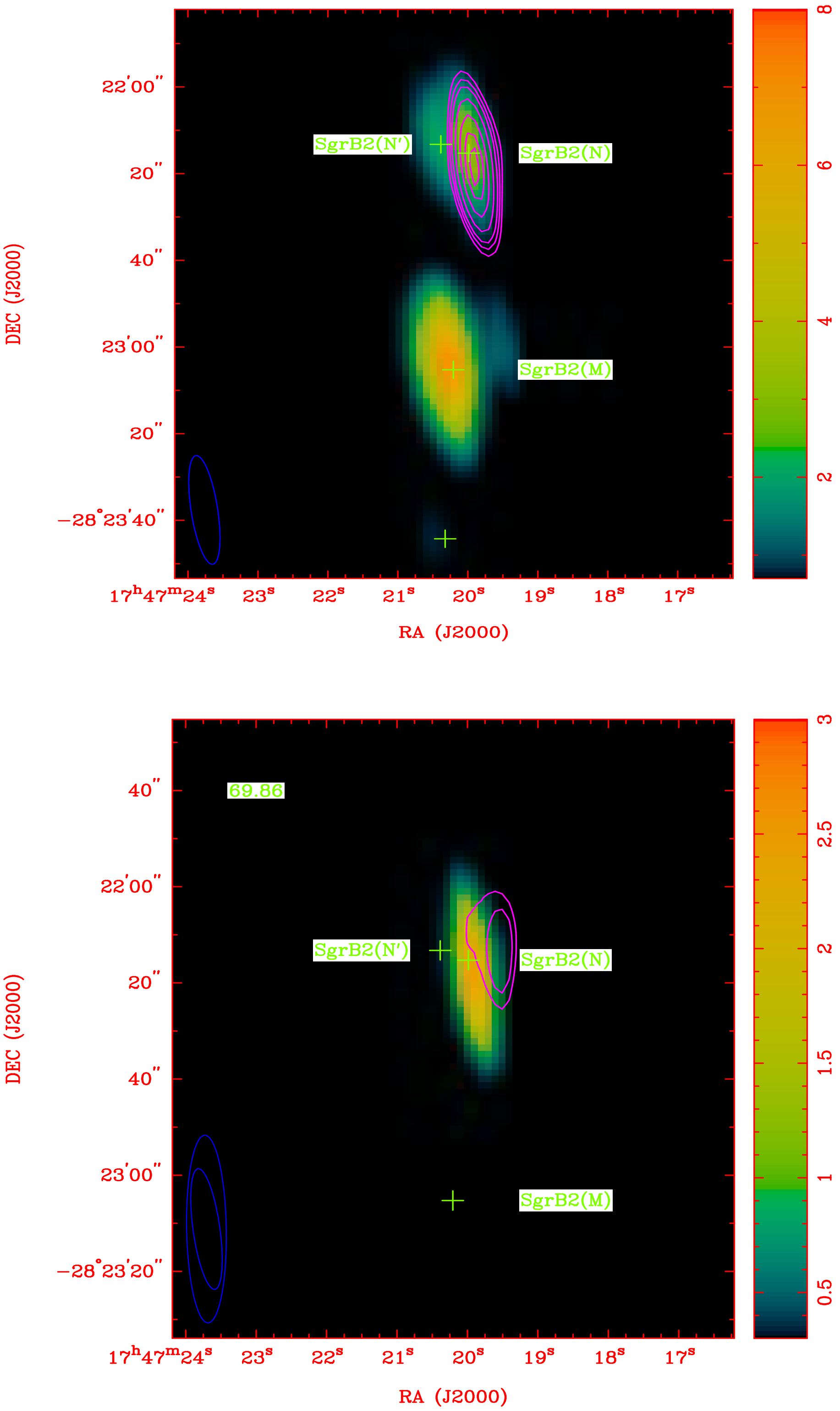


Figure 1: BIMA maps of CH_3OH and MeOEt in Sgr B2(N) (Charnley et al. 2001). The size of the synthesized beam in each case is given by the ellipses in the lower-left corner. (top) CH3OH $13_{-3} - 14_{-2}$ at 84.4 GHz (contours) plus 3-mm continuum (color scale). (bottom) MeOEt $12_{0,12} - 11_{1,11}$ at 79.6 GHz (contours) plus CH_3OH $13_{-3} - 14_{-2}$ (color scale). The number on the upper-left corner is the LSR velocity.

3.2 Organic molecules in our galactic center

(Sub)millimeter line surveys of well known sources, such as the dense cores in the Orion and Sagittarius molecular clouds (e.g. Schilke et al. 1997, 2000, Nummelin et al. 1998), show that molecules of considerable complexity can be found in these regions and others might yet have to be detected (Charnley et al. 2001). A large part of the molecular complexity found in these regions is due to gas-grain interactions. The sources mentioned above are examples of so-called "hot cores", dense ($> 10^6$ cm^{-3}), hot (~ 200 K) regions in the immediate vicinity of massive protostars. The high abundances of many molecular species found in hot cores cannot be explained by gas phase chemistry and one must invoke molecule formation on catalytic icy grain surfaces (e.g., van Dishoeck & Blake 1998, Ehrenfreund & Charnley 2000) during the cold dark cloud phase of these cores. Heating by the newly formed protostar and/or energetic processes such as outflows producing shock waves lead to evaporation of the grain mantles into the gas, which is followed by gas-phase reactions. Pathways to the formation of larger molecules include alkyl cation transfer (Charnley et al. 2001).

Figure 1 shows BIMA (Berkeley-Illinois-Maryland Array) observations near 3 mm wavelength of a methanol (CH_3OH) transition, the dust continuum emission, and the $12_{0,12}$–$11_{1,11}$ transition of methyl-ethyl-ether (MeOEt) toward the massive dense molecular cloud core Sagittarius B2(North) [Sgr B2(N)] near the Galactic center. These interferometer maps show a clear concentration of methanol around the Sgr B2(N) hot core (Figure 1, top). The Sgr B2(N) regions is also known as the "Large Molecule Heimat" (see Snyder 1997) due to the high concentrations and rich diversity of the complex organic molecules detected there. By contrast, few large organics are detected at Sgr B2(M) and this is generaly believed to be because B2(M) is much more dynamically and chemically evolved; Sgr B2(N) appears to have only recently 'switched on' (less than about 10^4 years) and the contents of its evaporated mantles have not yet been destroyed in gas phase reactions. This situation is evident in Figure 1 where MeOH and MeOEt are only present in the northern source. The map shown in Figure 1 (bottom) shows that the MeOEt emission has a distribution that is very similar to that of the methanol, as one might expect if these molecules are chemically linked (Charnley et al. 2001). The BIMA data indicate [MeOEt/H_2] abundance ratios of 10^{-10} – 10^{-9} in Sgr B2(N).

Radioastronomical observations are vital for the identification of large organic molecules in the interstellar medium and in cometary comae. Such observations help reconstructing the gas-grain chemical pathways in such regions.

4 Molecules in protoplanetary disks

In current scenarios of low mass star formation a protostar with an accretion disk and strong mass outflow is formed after gravitational collapse of a molecular cloud on a time-scale of 10^4–10^5 years (see, e.g., Lada 1991, Shu 1991). In its early evolutionary phases this protostar is still embedded in its placental cloud material. It then evolves into a T Tauri star and after $\sim 10^6$–10^7 years reaches the main sequence. During this phase, a planetary system may form. T Tauri stars are considered to resemble our sun when it was a few million years old. Studies of their surrounding gas and dust can therefore provide important clues on the early evolution of the solar nebula.

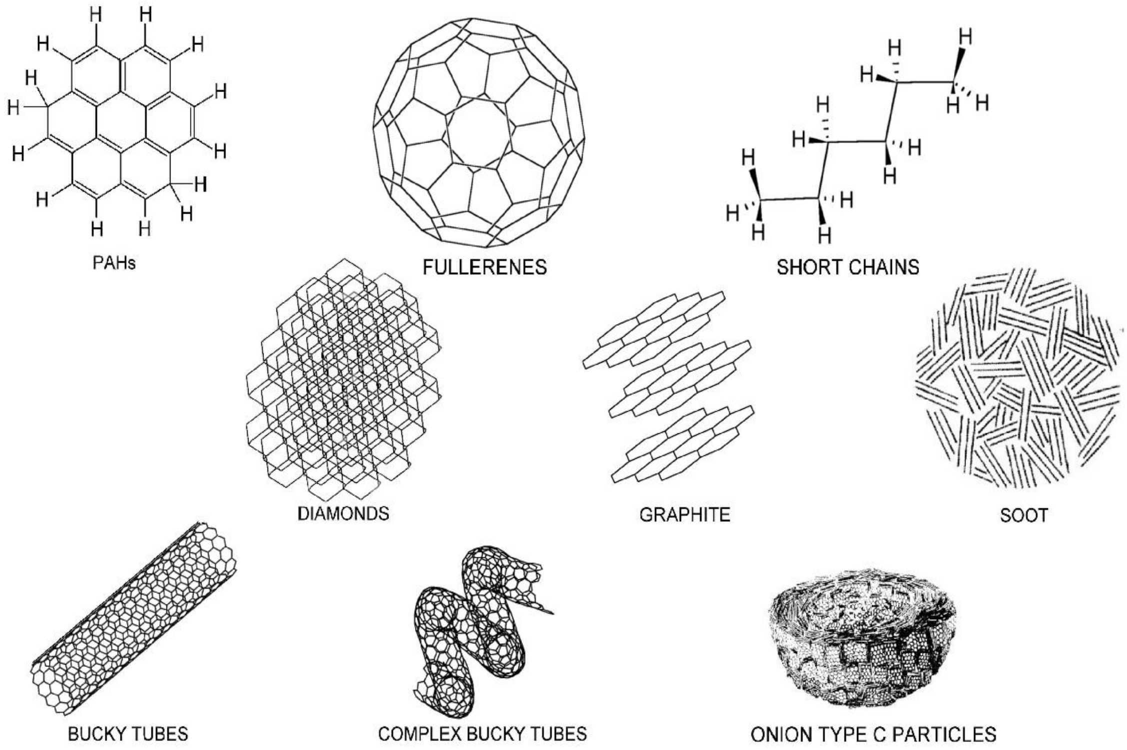
Infrared and millimeter surveys have shown that most T Tauri stars have circumstellar disks with masses of 10^{-3}–10^{-1} solar masses and sizes of 100–400 AU (see reviews by Beckwith & Sargent 1996, Dutrey et al. 1996, Mundy et al. 2000). Such disks provide a reservoir of gas and dust for the formation of potential planetary systems (Shu et al. 1993). For the purpose of discussing their chemistry, one may divide protoplanetary disks in a multi-layer structure consisting of a midplane, an intermediate region, and a surface region (Aikawa & Herbst 1999). The densities and radiation fields in the surface region are similar to interstellar photodissociation regions. In the warm upper atmosphere of the disks exposed to both the central star and the interstellar radiation field, the molecules are rapidly destroyed by photodissociation (Willacy & Langer 2000). The intermediate region has conditions similar to dense molecular clouds, where ion-molecule and neutral-neutral reactions occur in addition to photochemistry. The midplane of the disk cannot be penetrated by UV photons at all and molecules freeze out onto dust grain surfaces.

Determining the molecular composition of such protostellar disks provides information about the protosolar nebula and the evolution of our solar system. Dutrey et al. (1997) reported the detection of CN, HCN, HNC, CS, HCO^+, C_2H and H_2CO (ortho and para) in the protoplanetary disks of DM Tau and GG Tau. These systems are only 140 pc away and located in the outskirts of the Taurus molecular cloud complex. DM Tau is one of the oldest T Tauri stars in this region, whereas GG Tau is a young binary star. It was found that many of the above mentioned molecules are underabundant with respect to standard dense clouds. The relatively large abundances of CN and C_2H indicate a rich photon-dominated chemistry (Dutrey et al. 1997). It is worth pointing out that the small angular dimensions of the emission regions in question preclude detailed studies of the chemical and physical conditions on solar system size scales (i.e. less than 0.5 arcsec at the Taurus molecular cloud distance) with current millimeter-wavelength equipment. Future instruments, such as the Atacama Large Millimeter Array (ALMA), combine the necessary spatial resolution and high sensitivity to allow such observations resolving size scales of a few astronomical units (see, e.g. Menten 2000).

5 Diffuse clouds

Diffuse clouds are dominated by photochemistry. Such clouds have moderate extinctions (<1 mag) and densities of roughly 100–300 cm^{-3}. Interstellar extinction is measured in magnitude (mag) at a given wavelength and reflects the starlight which is absorbed and scattered by dust grains and reaches the observer dimmed. The Hubble Space Telescope (HST) has provided many accurate ultraviolet measurements of metals like C, O, N, Mg, Si, S, Cr, Fe, Ge, Zn, and Kr, greatly advancing our knowledge on the metallicity of diffuse gas clouds (e.g. Cardelli et al. 1993). In particular, measurements of the carbon abundance provide strong constraints on the budget available to form grains with carbonaceous mantles. Sightlines through diffuse clouds also allow measurements of extinction curves (Jenniskens & Greenberg 1993). With many such measurements available, it has become clear that the long wavelength part of the extinction curve ($\lambda > 2500$ Å) varies little from sightline to sightline, but that the converse is true for the short wavelength behavior, including the 2200 Å bump. These uncertainties very likely reflect changes in the composition and size distribution of (small) interstellar dust grains (Draine 1990).

Organic molecules present in the diffuse medium can originate via gas phase reactions, either in situ (Bettens & Herbst 1996) or by reactions in circumstellar envelopes followed by subsequent mixing into the diffuse medium, or by photoreactions of carbonaceous particles and sputtering by grain-grain collisions. Among the large organic molecules observed or suspected in diffuse clouds are polycyclic aromatic hydrocarbons (PAHs), fullerenes, carbon-chains, diamonds, amorphous carbon (hydrogenated and bare), and complex kerogen-type aromatic networks. The formation and distribution of large molecules in the gas and solid state is far from understood. In the envelopes of carbon-rich late-type stars, carbon is mostly locked in CO and C_2H_2. C_2H_2 molecules are precursors for soot formation, where PAHs might act as



PAHs FULLERENES SHORT CHAINS

DIAMONDS GRAPHITE SOOT

BUCKY TUBES COMPLEX BUCKY TUBES ONION TYPE C PARTICLES

Figure 2: Some of the various forms of carbon that are likely present in gaseous and solid state in the ISM and in solar system material.

intermediates (Frenklach & Feigelson 1989). The ubiquitous presence of aromatic structures in the ISM and in external galaxies has been well documented by numerous observations with the Infrared Space Observatory, or ISO (see special volume 315 of Astronomy & Astrophysics, 1996). Possible evidence for carbon-chains and fullerenes arises from the characterization of the Diffuse Interstellar Bands (DIBs) (Freivogel et al. 1994, Tulej et al. 1998, Foing & Ehrenfreund 1994, 1997). Diamonds were recently proposed to be the carriers of the 3.4 and 3.5 μm emission bands observed in planetary nebulae (Guillois et al. 1999) and hydrogenated amorphous carbon (HAC) seems to be responsible for the 2200 Å bump in the interstellar extinction curve (Mennella et al. 1998).

Carbonaceous dust in the interstellar medium may show considerable diversity and may include amorphous carbon (AC), hydrogenated amorphous carbon (HAC), coal, soot, quenched-carbonaceous condensates (QCC), diamonds, and other compounds (Henning & Salama 1998). The coexistence of PAHs and fullerenes together with complex carbonaceous dust suggests a common link and an evolutionary cycle that is dominated by energetic processing (Jenniskens et al 1993; Scott et al 1997). A detailed comparison of solid-state carbonaceous models of cosmic dust has been summarized by Papoular et al. (1996). Figure 2 displays the chemical structure of some carbon compounds which are likely to be present in diffuse clouds and other space environments.

6 The evolution of organic molecules during solar system formation

In comets and outer solar system asteroids, organic molecules formed in the pre-solar interstellar nebula may have survived solar system formation in relatively pristine form. Therefore, these small bodies carry important evidence on the formation of the solar system. A number of now extinct short-lived nuclides provide important information about the sources of solar system material and, moreover, are useful chronometers of chemical processes which have occurred in the early solar nebula (Wasserburg et al. 1996). Primitive meteorites contain dust grains that predate the solar system. Isotopic analysis shows that such grains are formed in stellar atmospheres and thus represent samples of ancient stardust (Zinner & Amari 1999). Isotopic analyses (e.g. of C, N, ^{26}Al, Sr, Zr, Mo etc.) of presolar grains allow reconstruction of the nucleosynthetic processes which occurred in the environment in which such particles were formed. Presolar material has been altered by chemical and physical processes in the solar nebula before becoming incorporated into small bodies. Dust and molecules have been affected by different processes dominating at various radial distances from the sun. It is assumed that the outer solar nebula was an environment of low temperature and pressure. Whereas heating and thermochemical reactions were important in the inner nebula, the outer solar nebula, where comets formed, was mainly dominated by UV photochemistry and ion-molecule reactions (Fegley 1999).

6.1 Comets

Small bodies of the solar system were formed in the region of the giant planets and beyond from remnant planetesimals which were not assembled into planets. Comets are amongst the most pristine objects and studies of their composition are thus of obvious interest for all models of the early solar system. The only way to measure the nuclear composition of a comet directly is via *in situ* measurements by a space probe such as the *Giotto* mission to comet Halley (Keller et al. 1987). Observations of the coma allow us in principle to deduce the molecular inventory of the nucleus, see Figure 3. Remote sensing observations of comets Hyakutake and Hale-Bopp have revolutionized our understanding of the volatile chemical inventory of comets and the interstellar-comet connection. Many new cometary molecules were discovered by IR and radio observations (Lis et al. 1997, Mumma 1997, Crovisier & Bockelee-Morvan 1999, Bockelee-Morvan & Rickman 2000, Irvine et al. 2000). Recent detections include SO, SO_2, HC_3N, NH_2CHO, HCOOH, and $HCOOCH_3$ (Bockelee-Morvan et al. 2000). Interesting to mention are also the upper limits for organic molecules such as glycine and ketene, which indicate that such molecules are not abundant in this type of comets (Crovisier et al. 1999). With a few exceptions, such as ethane (C_2H_6), $N^+{}_2$, CO^+, all molecules in the cometary coma are also observed in the interstellar medium.

Most of the current cometary inventory has been determined from remote sensing of the long period comets Halley, Hale-Bopp and Hyakutake. Much less is known about the composition of short-period comets. Interestingly, recent observations of such objects indicate significant chemical diversity in the giant planets region. Observations of comet 21P/Giacobini-Zinner show deficiencies of ethane and CO and comet Lee is strongly depleted in CO compared to the long-period comets Hale-Bopp, and Hyakutake (Mumma et al. 2000). A large amount of information is expected to be obtained from space missions currently on their way or on the launching pad for a rendezvous with a comet, such as STARDUST, CONTOUR and ROSETTA. On-board instrumentation on the ROSETTA spacecraft will measure the physical properties of comet Wirtanen and the chemical composition of its coma but there will also be an attempt to

Figure 3: The spectacular appearance of comet West showing the ion and dust tails observed at the Observatoire de Haute Provence, France. Comets as bright as this appear only once or twice in a decade. Future space missions to rendezvous a comet will strongly improve our knowledge on the organic inventory which may have seeded the early Earth.

land for the first time on a comet nucleus to perform in situ measurements. Such unprecedented encounters will strongly increase our knowledge on the chemistry and composition of comets.

6.2 Meteorites

Over a century ago, it was established that some meteorites contain carbonaceous material. These carbonaceous chondrites contain a few percent of carbon and some of them exhibit a large variety of organic compounds (Cronin & Chang 1993). The best studied carbonaceous chondrite to date is the Murchison meteorite, of CM type, which fell in Australia on 28 September 1969. Subsequent analyses using a variety of methods have shown that the Murchison meteorite contains over 70 different amino acids (Cronin & Chang 1993). It is generally thought that most meteorites, and in particular the CM type carbonaceous chondrites, originate from the asteroid belt. In fact, powdered samples of the Murchison meteorite heated up to 900 C show strong similarities in their reflectance spectra to C and G type asteroids, which points to an asteroidal origin (Hiroi et al. 1999). However, based on mineralogical and chemical evidence, it has recently been suggested that both CI and CM meteorites could also be fragments of comets (Campins & Swindle 1998, Lodders & Osborne 1999). The distinction between comets and asteroids is no longer clearly drawn, and several objects have currently a dual designation (Yeomans 2000). Understanding the link between small bodies, such as comets, asteroids and their fragments enables us to reconstruct the processes occurring during planet formation (Cruikshank 1997).

7 Implications for the origin of life on the Earth

Right after the formation of the Earth, about 4.5 x 10^9 years ago, the planet provided very hostile conditions for life to develop. Volcanic eruptions from the heated interior and external heavy bombardment by small bodies may have extinguished emerging life on a rapid timescale. The heavy bombardment phase, which has been scaled from the lunar record, ended about 3.8 x 10^9 ago. The first evidence for life follows 300 million years later and is provided by microfossils (Schopf 1993). Ion probe measurements of the carbon isotope composition of carbonaceous inclusions (within apatite grains) from the oldest known sediments (BIF banded-iron formation from Isua) showed isotopically light carbon, indicative of biological activity even 300 million years earlier (Mojzsis et al. 1996). Those results provide evidence for the emergence of life on Earth $\sim$ 3.8 x 10^9 years before present, just at the end of the late heavy bombardment phase. This leaves very little time for life to develop.

Today, research on the origin of life is an interdisciplinary field which, apart from biologists, involves chemists, physicists, geologists and astronomers. Numerous theories for the origin of life exist which are based either on a terrestrial or an extraterrestrial origin (McKay 1997). Ideas for a terrestrial origin of life are focussed on the spontaneous formation of stable polymers out of monomers. It has been shown that amino acids spontaneously form polypeptides in aqueous solution under certain conditions and RNA oligomers can spontaneously form on inorganic substances, such as clay structures. For detailed information on the organic chemistry leading to higher complexity and life, we refer to chapters 5,21 and 22 of this volume.

An extraterrestrial origin of life on Earth via cosmic delivery of living organisms (panspermia), as proposed already in 1903 by Arrhenius, appears unlikely. Indeed, some organisms (and in particular their spores) are able to survive in extreme conditions of temperature and radiation on Earth and it has been argued that such species could survive interplanetary travel (see Chapter 5). However, recent studies have shown that the survival potential for living entities embedded in comets, asteroids, and cosmic dust impacting on the early Earth is negligible (NRC Report 1998). In contrast, the possible transport of extraterrestrial organic material via infalling comets and asteroids is a serious possibility (Oro 1961, Chyba et al. 1990). The very narrow window between the end of the heavy bombardment phase and the evidence for primitive organisms favors the idea that impacting prebiotic matter could have been the first step to life. Though it cannot be excluded that organics and living organisms have developed locally in protected areas on the Earth's surface or within the oceans, a substantial fraction of the Earth's prebiotic inventory of organic molecules and water may have been of extraterrestrial origin. Impact studies show that in particular small particles can be gently decelerated by the Earth's atmosphere and may have brought intact organics to the early Earth (Anders 1989, Chyba et al. 1992).

The origin and development of life must be strongly dependent on the conditions of its host environment. One of the most important events in early Earth evolution is the formation of an atmosphere. The primitive atmosphere originating from the accumulation of gases released from the surface must be related in composition to volcanic emissions, whose composition, in turn, depends on the internal structure of the planet, such as the oxidation state of the upper mantle (Kastings 1993). Current evidence strongly favors the hot accretion model in which the Earth essentially formed in a differentiated state (Kastings 1993). In this case, non-reducing or mildly-reducing emissions, composed of CO_2 and N_2 (and only traces of other species), are predicted from the earliest times. Such an atmospheric composition is not favorable for the formation of abundant prebiotic molecules in contrast to the conditions for the Miller-Urey experiments (Miller 1957). These experiments showed that important biological molecules, including sugars and amino acids could be formed by spark discharge in an atmosphere of reducing conditions

Figure 4: 49,000 years ago a large meteor created the Barringer Meteor Crater near Flagstaff, Arizona (credit D. Roddy, LPI). In 1920, it was the first feature on Earth to be recognized as an impact crater. Today, over 100 terrestrial impact craters have been identified.

(containing CH_4, NH_3, H_2, H_2O). Exogeneous delivery of organics may have been therefore more important than the endogenous production of organics on Earth. Even today, tons of organic material is brought to Earth via small particles, so called micrometeorites. More than 120 major craters found on Earth show the effects of violent impacts from space; see Figure 4. For example the C/T (Cretaceous-Tertiary) boundary sediments are sedimentary deposits that accrued from the end of the Cretaceous period to the beginning of the Tertiary period. They are distributed world wide and are recognized as a unique signature of a large asteroidal impact event near Chicxulub in Mexico (Kyte 1998). The discovery of high concentrations of extraterrestrial Ir in KTB sediments and Cr ratios are consistent with a chondritic type impactor (Shukolykov & Lugmair 1998).

The early atmosphere contained little or no free oxygen. The oxygen concentration increased markedly near $2.0 \text{ x } 10^9$ years ago due to photosynthetic activity of microorganisms. Greenhouse warming by small amounts of CH_4 in the atmosphere may have formed an organic haze layer, which cooled the climate and protected primitive life from UV irradiation in the period $3.5\text{-}2.5 \text{ x } 10^9$ years (Pavlov et al. 2000). Recent analysis of precambrian sedimentary rocks have revealed a profound change in chemical reactions involving S and O in the atmosphere that occurred between 2.1×10^9 and 2.5×10^9 years ago (Farquhar et al. 2000). During this exact period the oxygen levels in the atmosphere strongly increased. The increase of oxygen in the atmosphere was a major step in the evolution of life on Earth.

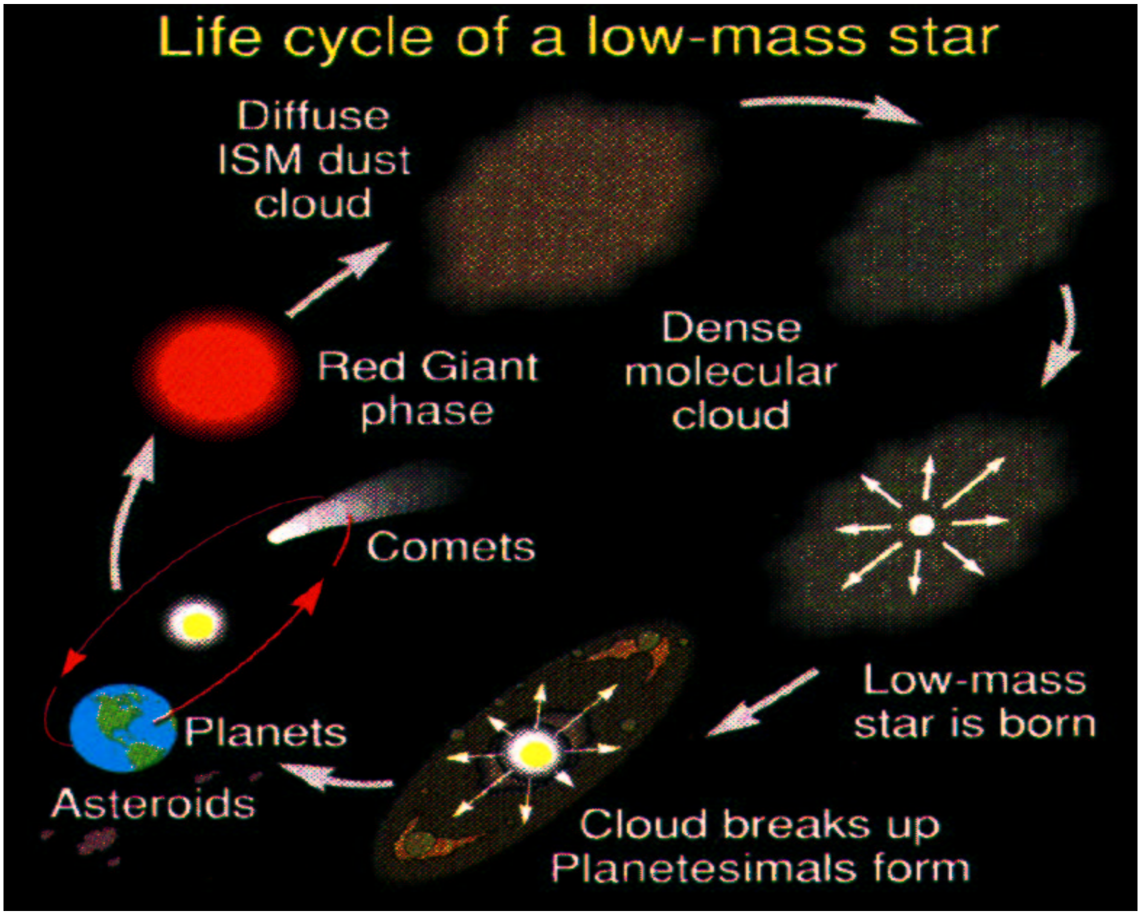


Figure 5: The cycle of a low-mass star (taken from Pendleton & Cruikshank, Sky and Telescope 87/3, 1994).

8 Conclusion

The biogenic elements (H, C, N, O, S, P) and organic matter are some of the major constituents of the universe. Observations over the entire electromagnetic spectrum revealed a rich diversity of organic matter which is formed in interstellar and circumstellar regions. The route from a diffuse cloud to a self-gravitating molecular cloud core may take tens of millions of years, see Figure 5. During this time, the interstellar gas undergoes strong chemical changes. To understand the process of star formation, one needs to comprehend the combined thermal and chemical balance of diffuse and dense interstellar gas clouds as they make their way from stellar winds to proto-stellar objects. The discoveries of protoplanetary disks around other stars, suggest that the processes which occurred in our solar nebula are common and the formation of solar systems like ours is not unique. The recent advances in the search for planets confirm this picture. The role of comets and other planetesimals in contributing organic matter to the primitive Earth and the prebiotic synthesis of biochemical compounds are major questions which remain to be answered in the future. Impacts may have led to extinction but may have also brought vital molecules to planet Earth, including organics and some H_2O. Valuable information may be obtained by future space missions investigating the existence of extinct and extant life on Mars, Europa and other bodies of the solar system and the search for new planets. Many of these questions will be answered by research groups which are participating in the NASA Origins program. To provide answers to the questions how life originated is of vital importance in the frame of recent planetary detections and the possible emergence of life elsewhere.

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