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Dust and Ice in the Interstellar Medium

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ABSTRACT

In this paper, we present an introduction to bare dust particles and grains covered by ice sheets in diffuse and dense interstellar clouds. It follows the life cycle of dust from its formation in stellar environments to its incorporation into the body of the Solar system. Dust particles play an important role in the physics and chemistry of many space environments. Regarding dust composition, two different populations are generally observed: silicate and carbonaceous dust. Energetic processing of ice layers with UV rays, X – rays or cosmic rays, after which the heat leads to the formation of complex organic molecules; some of them have prebiotic properties. Delivery of this organic fraction to the early Earth by meteorites and asteroids may have contributed to the origin of life.

Keywords- dust, Ice, interstellar medium, solar system, silicate dust, carbonaceous dust, UV rays, X-rays, cosmic rays.

I. INTRODUCTION

The Sun is a main sequence star, a period characterized by the fusion of hydrogen in the core of the star into helium. Like any other star with a mass no greater than eight solar masses, after about 5 □ 10^{9} years, the hydrogen in the core is depleted and hydrogen fusion of the upper layers (red giant phase) is initiated, followed by helium burning in the core (horizontal branch) and the combustion of hydrogen and helium in the upper layers (asymptotic giant branch or AGB, in which the star loses much of its mass). When the mass loss stops, star contraction begins and the temperature increases (postasymptotic giant phase). This contraction continues until the temperature is high enough to emit in the UV (planetary nebula), and nuclear fusion finishes when the star ends its days as a white dwarf.

The origin of silicate grains occurs in the atmospheres of AGB stars that eject dust grains (silicates and carbonaceous particles) into the interstellar medium. The birth of dust particles in space is, therefore, linked to the death of stars. Gas and dust in the interstellar medium constitute the so-called diffuse and dense clouds. Throughout their stay in the interstellar medium, a dust grain moves from the diffuse to the dense medium, and vice versa, until it is destroyed by shock waves during, e.g. a supernova explosion. In dense clouds, dust grains participate in star formation absorbing the excess energy generated during the gravitational collapse of a region in the cloud, and emit this energy in the IR range where the cloud is optically thin, allowing the release of energy. Conservation of angular momentum favors the formation of a disk around the protostar, which often evolves leading to planets, comets and asteroids. Dust grains are thus originated during the stellar death and their life ends when a new star is born. This lifecycle of dust is depicted in Fig.1.

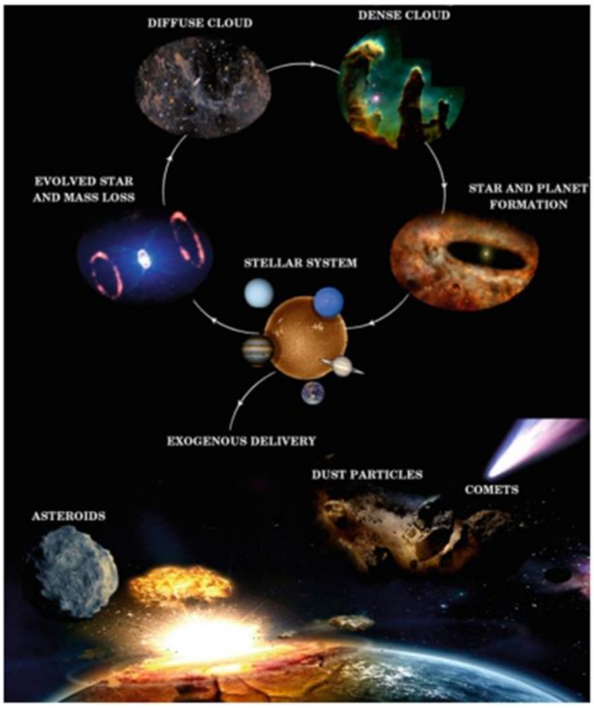

Fig. 1. The lifecycle of matter in the galaxy. Picture composition using images from NASA was kindly provided by G. A. Cruz Diaz

The interstellar medium, namely the space between stars, was thought to be empty but is now known to contain gas and dust. The number of interstellar molecules detected in the solid and gas phase is continuously increasing. To date, about 200 different species have been identified. The interstellar medium is, however, a harsh environment, where the high radiation field destroys the existing molecules and hinders the accretion of ice mantles onto dust grains because the temperatures are not sufficiently low. This environment is called the diffuse interstellar medium. On the other hand, the interiors of dense interstellar clouds, with densities above 10 particles , are preserved from the external ultraviolet (UV) radiation emitted by massive stars, and the typical temperatures below 20K permit the accretion of volatiles onto dust grains, thus forming ice mantles. Dense clouds are exposed to secondary UV-photons generated by cosmic-ray excitation of molecular hydrogen, which is expected to be no higher than 10 photons [1]. This weak UV-field is, however, expected to trigger photochemistry in the ice mantles, thus enriching their composition with more complex molecules. If the radiation dose is too high, the molecules desorbing to the gas phase will also be destroyed, as it often occurs in diffuse clouds. During the early stages of stellar evolution, the outer parts of circumstellar regions offer a new scenario for ice mantle processing, where the main radiation sources are the central object and the surrounding interstellar field. The coagulation of grains leading to planetesimals and cometesimals protects the photoproducts from subsequent irradiation. In those environments, radiation is driven by cosmic rays (protons and heavier ions covering a wide energy range), UV photons, and X-rays; the later are expected to dominate the photon processing during the first 300 Myr of solar type stars [2]. Space missions to comets and asteroids enrich our understanding of the formation of our solar system and also serve to characterize the most primitive matter preserved in these small bodies. The delivery of these materials via comets, (micro-) meteorites, and interplanetary dust particles to Earth enables their investigation in the laboratory. In this chapter, the dust and ice present in the interstellar medium are introduced.

The use of spectroscopic techniques for the observation of dust particles in space, in particular infrared (IR) and UV spectroscopy, allow the study of their composition and physical properties. A proper interpretation of the observed spectral data is done by comparison to laboratory analogs produced under mimicked astrophysical conditions. A recent and excellent review on the physics and chemistry of ice [4]. Some of the topics presented in this chapter were discussed [3].

II. THE IMPORTANCE OF DUST IN SPACE

Ice mantles on dust grains may act as coolants during star formation, leading to smaller stars like our Sun. Dust particles also serve as catalysts for the production of molecules [16], and other species present in the ice such as, detected by IR observations. Some complex molecules detected toward hot cores/corinos, where high/low mass protostars are forming, respectively, are indicative of ice mantle sublimation during warm-up of the dust. Indeed, in many cases, the molecular abundances observed by radio astronomers cannot be explained solely by reactions in the gas phase. A bare dust grain consists of a silicate and/or a carbonaceous core. The composition of the dust and the accreted ice layers is related to the materials and atomic abundances in the environment where they were formed. Relative to hydrogen, the cosmic abundances of oxygen, carbon, and nitrogen are 4.57 × 10, 2.14 × 10, and 0.66 × 10, respectively [5]. Most of the observed solid carbon comprised in dust particles is a type of hydrogenated amorphous carbon, known as a-C:H, or HAC in the astrophysics community. Amorphous carbon consists of an amorphous matrix composed of sp2, sp3, and even sp1, hybridized C atoms. a-C stands for amorphous carbon that contains less than 20 % hydrogen, while hydrogenated amorphous carbon, abbreviated as a-C:H, contains between 20 % and 60 % hydrogen, and therefore has a low number of − bonds. The macroscopic properties of amorphous carbon are linked to its H content, / bonding ratio, and the degree of sp2 clustering. Hydrogen is also abundant in ice mantles, contributing to the formation of water molecules on the dust surface and other molecules like methanol, OH, ammonia, NH3, or methane. While a diatomic molecule, CO, is the most abundant C-containing species observed in the gas phase, larger Cspecies include the fullerenes detected toward planetary nebulae [6; 7]. and the presence of polyaromatic hydrocarbons was postulated based on the observed IR emission lines of aromatic character.

Oxygen is a key component in silicate grains and participates in the formation of the most abundant molecules detected in the gas phase and the ice mantles, these include O, CO, and. Although some nitrogen-bearing species are routinely detected in the gas phase toward dense clouds or circumstellar environments, the presence of nitrogen in solids is rather elusive because N-bonds have intrinsically low band strengths in the IR. Relatively low abundances of, or HNCO were reported in icy dust. Nevertheless, nitrogen is essential for the formation of prebiotic molecules. In particular, the presence of in ice analogs submitted to radiation leads to a very complex network of reactions in laboratory simulations.

III. SILICATE DUST

IR spectroscopy allows the detection of silicate bands in emission and absorption, providing an estimation of the silicate dust column densities along the line of sight, in Si atoms, the dust temperature, and the silicate composition and structure, depending on the environment [8]. Two broad bands are observed near 10 and 18 µm (1 000 and 550) toward various interstellar regions, which correspond to the Si–O stretching and O–Si–O deformation modes in silicates, respectively. The processes involved in the evolution of silicates are heating, photon and ion irradiation, shocks, destruction and recondensation.

It has been observed that olivine's, with chemical formula SiO4, and pyroxenes, that consist of (Si), are usually the most abundant silicates. As it was mentioned above, amorphous silicate grains are condensed in oxygen-rich AGB stars, with a small proportion of crystalline silicates [10]. While amorphous silicates are abundant in the diffuse interstellar medium, crystalline silicates dominate in circumstellar disks and cometary nuclei and comae. For a long time, this transition from amorphous to crystalline silicates remained a mistery. Observations showed that crystalline silicates can be synthesized in the surface of an inner disk by thermal annealing during a stellar outburst [11].

IV. CARBONACEOUS DUST

The presence of various types of carbon-bearing dust is noticeable thanks to the observations performed in a broad spectral range. The observed band at around 2175 Å, called the "UV hump", is explained by absorption of interstellar carbon grains with sp2 hybridization. The presence of various dust components and large molecules was inferred from the emission spectra observed in the diffuse medium:

These are: the aromatic infrared bands (AIBs), the very small grains (VSGs) of 1–10nm in radius, and the big grains (BG) of more than 10 nm in radius composed of silicates/carbon. The Diffuse Interstellar Bands (DIBs) in the visible are associated to large molecules. For an introductory review on dust (see Dartois 2005 and references therein). The 3.4-m characteristic of carbon granules in the diffuse medium toward dense interstellar clouds was not noticed in the mid-IR band. It was suggested that the dust particles in dense clouds should include a more dehydrogenated form of solid carbon. Other galaxies were also found to have this IR absorption [4]. It can be decomposed in three bands peaking near 2 923, 2 958, and 2 865 cm-1 that are related to the asymmetric -, asymmetric, and symmetric- stretching modes in aliphatic compounds, respectively.

Other absorptions were observed near 6.85 µm (around 1 460) and 7.25 µm (around 1 380), which are attributed to CH bending modes of the same aliphatic material. A laboratory photo produced a-C:H made from photo processing of simple aliphatic molecules can reproduce all the observed spectral features which indicates a similar composition. Carbon grains in the diffuse ISM could therefore be a form of "polymerlike" a-C:H that contains a rather low amount of oxygen. This material is essentially made of hydrocarbon chains with olefinic and aliphatic bonds in the proportion / ≈ 2. Occasionally, small aromatic units of 1 or 2 rings join its composition [5]. This characterization differs from previous works describing a highly aromatic material. Because the collision time scale is too large in the interstellar medium to form a stable polymer, carbon grains likely originated in a more dense environment. It is believed that carbon dust is produced in stellar eject and spread over the interstellar medium. Various types of amorphous carbon with different aromatic and hydrogen contents are also present in small bodies of the solar system, such as comets, meteorites and interplanetary dust particles [10].

V. ICE MANTLES

As it was brought forward in Sect.1, the molecular composition of interstellar and pre-cometary ice is mainly O, and the less abundant species include CO, OH, OCN-, OCS, CO, HCOOH,, and or NH+ 4 [12; 13]. The precise structure of the icy phase in dust grains is still an open question. A water-rich and a water-poor phase were proposed, which were probably formed in a H-dominated and later in a CO-controlled environment, respectively [14]. It is often not clear if the different molecular ice components are intimately mixed or segregated in a multilayer structure. In the case of, there is evidence for the absence of a pure and amorphous phase [15].

VI. ICE PROCESSES

The formation of the ice mantle is controlled by the accumulation and expulsion of molecules On cold dust, these processes will therefore shape dense interstellar evolution clouds and especially star-forming regions [12]. Laboratory Simulation of these processes under relevant astrophysical conditions is needed For our understanding, an adequate interpretation of the observations relative to the cold Interstellar regions require a good understanding of the processes that occur interface between solids and gas phase. Most of the observations are made and detected in radio The molecules in the dust gas are often referred to as a kind of “black box” in the gas Phasic reactions alone cannot explain the observed molecular abundances Fig. 2.

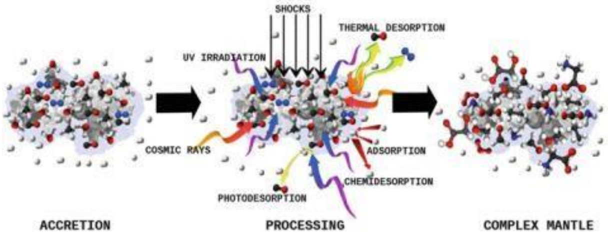

Fig. 2. The processes occurring on ice mantles are presumably leading to the formation of more complex species, as observed in laboratory simulations. Image provided by G. A. Cruz-Díaz

In the cold interiors of dark molecular clouds, thermal desorption should be negligible, and therefore the accretion of molecules (other than) on dust particles leads to their depletion in the gas. Although carbon monoxide should deplete below 20 K, it is observed in the gas toward cold clouds at densities below ≈ 3 × 4 [16]. Other molecules like methanol and formaldehyde are also observed in cold regions[11]. This suggests that there must be a non-thermal desorption mechanism operating in dark clouds. The release of chemical energy was proposed as a non-thermal desorption mechanism [17].

VII. PRESENCE OF ORGANICS MADE FROM UV-PHOTO PROCESSING OF ICE IN SMALL SOLAR SYSTEM BODIES

Comets and primitive meteorites act as “time machines” that allow us to take a glimpse at our solar nebula. These objects contain carbon matter that might predate our solar nebula and compounds that were formed at the early stages of our solar system. We will discuss that pre-cometary icy dust likely hosted the molecules that are found in organic refractory residues. These species are a minor component in carbonaceous chondrites. Halley-type comets might still preserve this material of prebiotic interest, while aqueous alteration of the indigenous organic material in asteroids likely changed its chemical composition. The amino acids and polyols detected in the Murchison and Murray meteorites, with high D/H abundance ratios that suggest a formation at very low temperatures, were probably formed by ice processing. Several diamino acids, amino acids with two amino groups in their structure, found in irradiated ice residues, were also detected in Murchison [15].

VIII. THE DELIVERY OF EXOGENOUS ORGANIC MATTER AND THE ORIGIN OF LIFE ON EARTH

Shortly after the formation of the Earth, a large number of minor bodies impacted on its surface during the late heavy bombardment about 3.9 Gyr ago. Comets experienced a migration from their original location between Uranus and Neptune due to gravitational pulls of planetesimals. According to our knowledge on the actual composition of comets and asteroids, we expect that their loads occasionally contained prebiotic species that were delivered to our young planet with some degree of alteration. Estimates based on noble metals and gas contents provide a value of the extraterrestrial mass accreted by the Earth a after core formation: 2.7·10 kg. Asteroids would be the main contributors to this mass while comets would only account for 0.1 % (Dauphas and Marty 2002). The D/H ratio of water in asteroids is close to the value in the Earth’s oceans, while Oort cloud comets display significantly higher values. However, the D/H values in Jupiter family comets and main-belt comets appears to be similar to asteroids [7]. Although these statistics are still rather poor, this might be an indication of the relative contribution of matter from these bodies to our home planet.

IX. CONCLUSION

The results of the findings show that according to the composition and dust, two different populations are observed: silicate and carbonaceous fine dust. The origin of silicate grains occurs in the atmosphere of stars, which ejects dust grains (silicate and carbon particles) into the interstellar medium. Gas and dust in the interstellar medium are called diffuse and dense clouds. During their stay in the interstellar medium, fine dust particles move from the diffuse medium to the dense medium and vice versa, until they are destroyed by the shock during it. to be Dust grains originate during the death of a star, and their life ends when a star is born. The interstellar medium, the space between stars, was empty, but is now known to contain gas and dust. The number of interstellar molecules identified in the solid and gas phase is constantly increasing. So far, about 200

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different species have been identified. It becomes dusty from the accumulation of particles because the temperature is not low enough.This environment is called diffuse interstellar medium. On the other hand, dense interstellar cloud interiors, with densities above 10 particles, are shielded from external ultraviolet (UV) radiation.

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