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Interstellar Chemistry

Pascale Ehrenfreund

Leiden Observatory, Leiden, The Netherlands

The space between the stars, called the interstellar medium (ISM), is composed primarily of H and He gases incorporating a small percentage of small micron-sized particles. Interstellar clouds constitute a few per cent of galactic mass and are enriched by material ejected from evolved dying stars. Astronomical observations of interstellar clouds have shown dust and molecules widespread in our Milky Way galaxy, as well as distant galaxies [1–3]. The fundamental cloud parameters such as temperature and density can vary substantially. Two main types of interstellar clouds drive molecular synthesis. Cold dark clouds are characterized by very low temperatures ($\sim$10 K) leading to a freeze out of practically all species (except H_2 and He). The higher density of dark clouds ($\sim 10^6$ atoms cm^{-3}) attenuates UV radiation offering an environment where molecules can efficiently form through gas-phase and surface reactions. Surface catalysis on solid interstellar particles enables molecule formation and chemical pathways that cannot proceed in the gas phase owing to reaction barriers [4]. Many molecules have been identified through infrared spectroscopy in ice mantles covering small interstellar dust particles (see Gibb et al. 2004 for a review [5]). Dominated by H_2O, those ice mantles also contain substantial amounts of CO_2, CO and CH_3OH, with smaller admixtures of CH_4, NH_3, H_2CO and HCOOH [6, 7]. The median ice composition H_2O:CO:CO_2:CH_3OH:NH_3:CH_4:XCN is 100:29:29:3:5:5:0.3 and 100:13:13:4:5:2:0.6 towards low- and high-mass protostars, respectively, and 100:31:38:4:-:-:- in cloud cores [8]. Laboratory simulations indicate that thermal and UV radiation processing close to the protostars results in ice desorption, ice segregation and the formation of complex organic molecules such as quinones and even dipeptides [9, 10].

Diffuse interstellar clouds are characterized by low densities ($\sim 10^3$ atoms cm^{-3}) and temperatures of $\sim$100 K. Ion–molecule reactions, dissociative recombination with electrons, radiative association reactions and neutral–neutral reactions contribute to gas-phase processes and influence molecule formation in those regions. Many small molecules, including CO, CH, CN, OH, C_2, C_3 and C_3H_2, have been observed [11, 12], together with a high fraction of polycyclic aromatic hydrocarbons (PAHs) [2]. Dust particles contain macromolecular aromatic networks evidenced by a ubiquitous strong UV absorption band at 2175 Å [13]. Amorphous carbon, hydrogenated amorphous carbon, diamonds, refractory organics and carbonaceous networks such as coal, soot and graphite and quenched carbonaceous condensates have been proposed as possible carbon compounds [14, 15]. In diffuse interstellar clouds, dust interacts with hot gas, UV radiation and cosmic rays, and evolves or gets destroyed in shocks and by sputtering. Strong differences in the dust component of dense and diffuse interstellar clouds exclude rapid cycling of cloud material [16].

In summary, a large number of complex molecules in the gas phase have been identified through infrared, radio, millimetre and sub-millimetre observations. Currently, > 180 molecules are detected in the interstellar and circumstellar gas although some of them are only tentatively identified and need confirmation. More than 50 molecules are found in extragalactic sources (http://www.astro.uni-koeln.de). H_2 is by far the most abundant molecule in cold interstellar regions, followed by CO, the most abundant carbon-containing species, with $CO/H_2 \sim 10^{-4}$. The chemical variety of molecules includes nitriles, aldehydes, alcohols, acids, ethers, ketones, amines and amides, as well as long-chain hydrocarbons.

Circumstellar envelopes, regarded as the largest factories of carbon chemistry in space, are where small carbon compounds are converted to larger species and into solid aromatic networks such as soot [17]. Processes analogous to soot formation on terrestrial environments are assumed to form robust coal-like material. Laboratory simulations showed that the temperature in the circumstellar condensation zone determines the formation pathway of carbonaceous particles with lower temperatures ($<$1700K) producing PAHs with three to five aromatic rings [18] compared to temperatures above 3500 K that favour the production of fullerene compounds. The detection of C_{60} and C_{70} fullerene molecules was recently reported in a protoplanetary nebula by Cami et al. [19]. Molecular synthesis may occur in the circumstellar environment on timescales as short as a few hundred years.

Interstellar chemistry shapes the raw material for the formation of stars and planets. The gravitational collapse of an interstellar cloud led to the formation of the protosolar nebula approximately 4.6 billion years ago. From this solar nebula, planets and small bodies formed within less than 50 million years. Data from recent space missions, such as the Spitzer telescope, Herschel, Stardust and Deep Impact, show a dynamic environment of the solar nebula with the simultaneous presence of gas, particles and energetic processes, including shock waves, lightning and radiation. The carbonaceous inventory of our solar system has therefore experienced a variety of conditions and contains a mixture of material that was newly formed in the solar nebula as well as interstellar material that experienced high temperatures and radiation. Some pristine cloud material with significant interstellar heritage has survived as evidenced from laboratory studies of extraterrestrial material. Understanding the evolution of interstellar material and dust cycling provides important insights into the nature of the material that is later incorporated into planet and small bodies. The latter, including comets, asteroids and their fragments, carbonaceous meteorites and micrometeorites, contain a variety of molecules including biomarkers that transported raw material for life to the young planets via impacts in the early history of the solar system [20]. Experiments in low Earth orbit enable to simulate true space conditions and have contributed important results on the stability and photochemistry of organic compounds, biomarkers and microbes in space environment in the last decade.

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