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INVITED REVIEW

Organic matter in space: from star dust to the Solar System

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Abstract Organic compounds of high degree of complexity are now known to be widespread in the Universe, ranging from objects in our Solar System to distant galaxies. Through the techniques of millimeter-wave spectroscopy, over 140 molecules have been identified through their rotational transitions. Space infrared spectroscopy has detected the stretching and bending modes of compounds with aromatic and aliphatic structures. Analyses of samples of meteorites, comets, asteroids, and interplanetary dust also revealed a rich content of organic substances, some of which could be of extra-solar origin. We review the current state of understanding of the origin, evolution, nature, and distribution of organic matter in space. Also discussed are a number of unexplained astronomical phenomena whose origins could be traced to organic carriers.

Keywords Solar System · Stellar evolution · Infrared spectroscopy · Organic matter

1 Introduction

Although carbon is the 4th most abundant element in the Universe, the possibility of the widespread presence of organic matter in space was not seriously contemplated because the general perception was that the space density is too low for the synthesis of complex molecules. It was only since the 1970s after millimeter-wave spectroscopy has detected an increasing number of gas-phase carbon-based molecules in the interstellar medium (ISM) that astrochemistry has become a respectable discipline. The detection of molecules in the outflow of evolved stars also led to the realization that molecules can form in the low density environment of stellar winds, soon after the element carbon was synthesized by nuclear reactions in the stellar core, dredged up to the surface, and released from the atmosphere.

While the millimeter-wave technique is capable of detecting molecules consisting of over a dozen atoms, the high degree of complexity of interstellar organics was not appreciated until the development of astronomical infrared spectroscopy. A family of strong infrared emission bands at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.7 μm were first detected by the *Kuiper Airborne Observatory* (*KAO*) in the young carbon-rich planetary nebula NGC 7027 (Russell et al. 1977) and reflection nebula HD 44179 (Russell et al. 1978), and are now widely observed in H II regions, reflection nebulae, planetary nebulae, proto-planetary nebulae, and the diffuse ISM of our own and other galaxies (see Fig. 1). The widths of the features are much broader than molecular linewidths broadened by Doppler effects or turbulence and therefore they are designated as emission bands. Solar System objects, such as carbonaceous meteorites, interplanetary dust particles, and Martian rocks are also known to display these features. The energy emitted in these bands can be a significant fraction of the total dust continuum energy output of galaxies, and the identification of the carriers of these features is therefore important for the understanding of the chemical makeup of the ISM and galaxies.

The fact that the strengths of these infrared emission features correlate with the C/O ratio of planetary nebulae suggests a carbon-based carrier. Comparison with laboratory infrared spectroscopy of organic compounds has led to the identification that these features arise from stretching and bending modes of various CH and CC bonds in aromatic hydrocarbons (Duley and Williams 1981). For this reason, these strong infrared emission features are now known as

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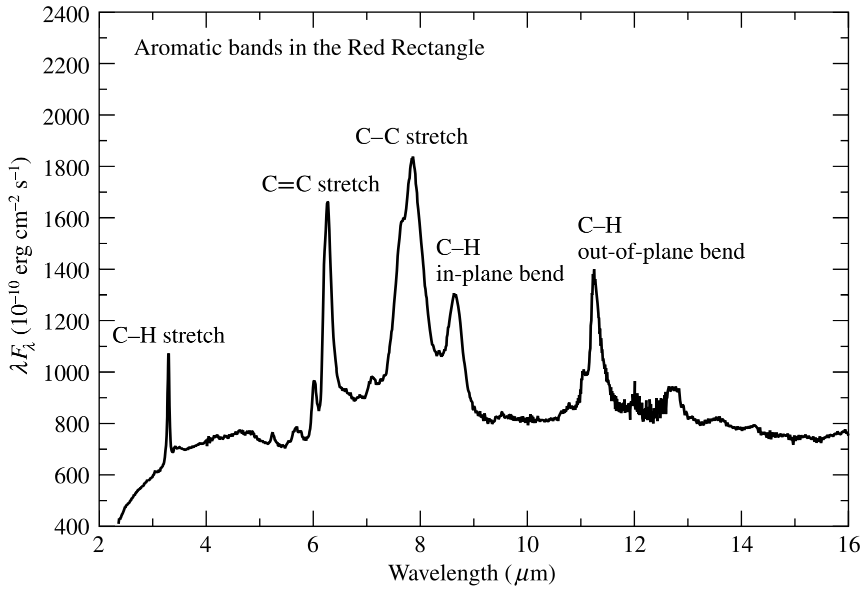

Fig. 1 The aromatic infrared bands (AIB) are prominent in HD 44179 (the Red Rectangle), a reflection nebula surrounding a B8-A0 central star in the late stages of stellar evolution. The vibrational modes of the aromatic units are identified in this *Infrared Space Observatory* (*ISO*) SWS01 and SWS06 spectrum

the aromatic infrared bands (AIB). The detection of aromatic compounds has led to the appreciation that all forms of carbon, including graphite, diamond, fullerene, carbyne) also exist in space (Henning and Salama 1998). A review of organic molecules in space was previously given by Ehrenfreund and Charnley (2000).

In this review, we summarize our present understanding of the presence of organic matter in the diffuse ISM, in the circumstellar environment, and in the Solar System. The possibility of a number of unexplained astronomical phenomena that may be due to organic compounds is also discussed. The chemical structures and possible laboratory analogs of extraterrestrial organics are presented. Near the end of the article, some speculations on the origin of these compounds and the possible links between stars and the Solar System are offered.

2 Organic molecules in the gas phase

As of 2008, more than 140 gas-phase molecules have been detected in the interstellar medium, including over 60 in the circumstellar envelopes of late-type stars. Most of these molecules were detected through their rotational transitions in the mm or sub-mm regions. The detected species cover all kinds of organic molecules, including hydrocarbons (e.g., methane CH_4, acetylene C_2H_2, ethylene C_2H_4), alcohols (e.g., methanol CH_3OH, ethanol C_2H_5OH, vinyl alcohol $H_2C{=}CHOH$), acids (e.g., formic acid HCOOH, acetic acid CH_3COOH), aldehydes (e.g., formaldehyde H_2CO, acetaldehyde CH_3CHO, propenal $CH_2{=}CHCHO$, propanal CH_3CH_2CHO), ketones (e.g., ethenone $H_2C{=}CO$, acetone, CH_3COCH_3), amines (e.g., methylamine CH_3NH_2, cyanamide NH_2CN, formamide NH_2CHO), ethers (e.g., dimethyl ether CH_3OCH_3, ethyl methyl ether $CH_3OC_2H_5$), etc. Of particular interest are prebiotic molecules leading to the formation of proteins, carbohydrates, nucleic acids, and lipids. The simplest sugar, glycolaldehyde (CH_2OHCHO), has been detected (Hollis et al. 2000). Active searches are now underway for the simplest amino acid glycine (NH_2CH_2COOH) (Kuan et al. 2003a; Snyder et al. 2005) and for the parents of the bases that constitute the structural units of DNA and RNA, such as purine (c–$C_5H_4N_4$) and pyrimidine (c–$C_4H_4N_2$) (Kuan et al. 2003b). Pyrimidine is the base contained in cytosine (DNA and RNA), thymine (DNA), and uracil (RNA), whereas purine is the base for adenine (DNA and RNA) and guanine (DNA and RNA). Although extraterrestrial nucleobases have been found in meteorites (Sect. 5.1), they are yet to be detected in the ISM.

Other large molecules detected in recent years include ethylene glycol ($HOCH_2CH_2OH$) (Hollis et al. 2002), propenal (CH_2CHCHO) and propanal (CH_3CH_2CHO) (Hollis et al. 2004), acetone (CH_3COCH_3) (Friedel et al. 2005), cyanoallene (CH_2CCHCN) (Lovas et al. 2006), acetamide (CH_3CONH_2) (Hollis et al. 2006a), cyanoformaldehyde (CNCHO) (Remijan et al. 2008), and cyclopropenone (c–H_2C_3O) (Hollis et al. 2006b). These detections were made possible by the construction of large single-dish telescopes (e.g., the 100-m Green Bank Telescope) and improving receiver sensitivities.

The detections of ring species such as cyclopropynylidyne (c–C_3H), cyclopropenylidene (c–C_3H_2), ethylene oxide (c–C_2H_4O), etc., raise the possibility of the existence of other biochemically important ring molecules. Planar rings containing other heavy elements (N, O, S) in addition to C play a fundamental role in biochemistry. Examples of these ring structures include furan (C_4H_4O), pyrrole (C_4H_5N), and imidazole ($C_3H_4N_2$). They are 5-membered rings with