

Delivery of Complex Organic Compounds from Evolved Stars to the Solar System

Sun Kwok

Received: 3 August 2011 / Accepted: 16 October 2011 /

Published online: 3 December 2011

© The Author(s) 2011. This article is published with open access at Springerlink.com

Abstract Stars in the late stages of evolution are able to synthesize complex organic compounds with aromatic and aliphatic structures over very short time scales. These compounds are ejected into the interstellar medium and distributed throughout the Galaxy. The structures of these compounds are similar to the insoluble organic matter found in meteorites. In this paper, we discuss to what extent stellar organics has enriched the primordial Solar System and possibly the early Earth.

Keywords Interstellar medium · Planetary nebulae · Asymptotic giant branch stars · Solar system · Meteorites · Pre-solar grains · Interplanetary dust particles

Introduction

Since the Millar-Urey experiment, it has been widely believed that life on Earth originated from simple molecules and developed in chemical complexity in a primordial soup under the rules of chemistry. In the past 30 years, an increasing number of organic molecules in the interstellar medium have been discovered by astronomical spectroscopic observations through their rotational and vibrational transitions (Kwok 2007). Consequently, there have been questions raised on whether interstellar organics play a role in the origin of life (Ehrenfreund and Charnley 2000). We now know that complex organics are everywhere in the Universe. Spectral signatures of aromatic compounds have been detected in the Solar System, stars, interstellar clouds, diffuse interstellar medium, and in external galaxies (Kwok 2011). Were these organics synthesized in situ in the Solar System and in interstellar clouds? In this paper, we offer the suggestion that organics are produced in large quantities in the circumstellar envelopes of evolved stars, and these organics are being distributed throughout the Galaxy via stellar winds. The early Solar System was likely to have been chemically enriched by some of these stellar materials.

S. Kwok (✉)

The University of Hong Kong, Hong Kong, China
e-mail: sunkwok@hku.hk

Synthesis of Complex Organics by Planetary Nebulae

Soon after the nucleosynthesis of the element carbon, stars on the asymptotic giant branch (AGB) have been observed to have synthesized over 60 different gas-phase molecules in their stellar winds (Olofsson 1997). These molecules include inorganics, organics, radicals, chains, and rings. Just before the stellar winds completely deplete the hydrogen envelope, acetylenes begin to form (Volk et al. 2000). This is followed by the formation of diacetylene, triacetylene, and benzene (Cernicharo et al. 2001). In the following evolutionary stage (called the proto-planetary nebulae phase), the first spectral signatures of aromatic compounds appear. The 3.3, 6.2, 7.7, 8.6, and 11.3 μm aromatic stretching and bending modes first make their appearance during the proto-planetary nebulae phase, and are found to become stronger in the subsequent planetary nebulae (Kwok 2000) phase (Fig. 1). These aromatic features are accompanied by aliphatic features at 3.4 and 6.9 μm in the spectra of proto-planetary nebulae. The detection of out-of-plane C-H bending modes at 12.1, 12.4, and 13.3 μm suggests that the aromatic rings are not all connected to each other and there are many exposed edges of the rings (Kwok et al. 1999). Also present in the spectra of proto-planetary nebulae are broad plateau emission features at 8 and 12 μm which are due to collections of in-plane and out-of-plane bending modes of aliphatic chains (Kwok et al. 2001).

These observations suggest that even under the extremely low density environment of the circumstellar envelopes, complex organics can be synthesized. One possible scenario is that starting from acetylene, these linear molecules bend to form benzene, and all kinds of aliphatic chains get attached to the rings. The aromatic rings grow in size, possibly as the result of photochemistry. Since we know the evolutionary and dynamical timescales of the AGB ($\sim 10^4$ yr), proto-planetary nebulae ($\sim 10^3$ yr), and planetary nebulae ($\sim 10^4$ yr) stages,

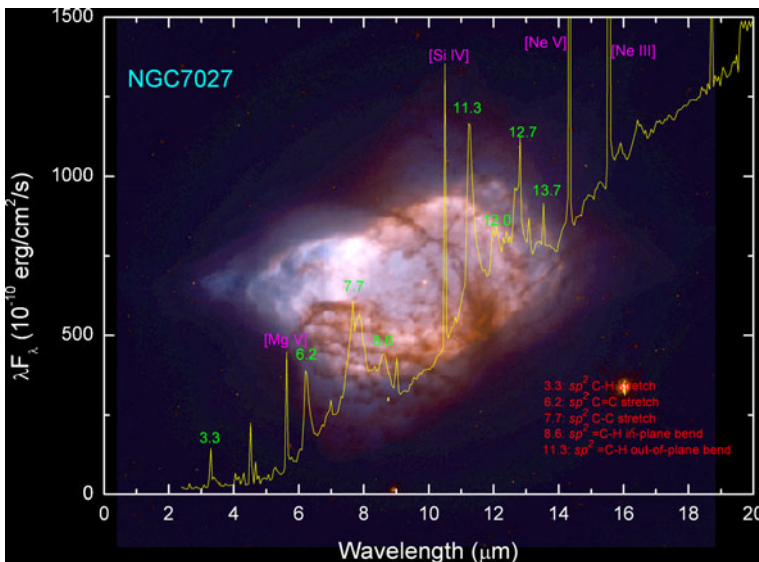


Fig. 1 Infrared Space Observatory spectrum of the planetary nebula NGC 7027 superimposed on the Hubble Space Telescope image of the object. The aromatic infrared bands (AIB) are marked in green. The identifications of these bands are given in the legend. The lines labeled in purple are atomic lines. The strengths of the AIBs show that aromatic compounds are being produced in large quantities

these time scales constrains the chemical timescales that the synthesis must take place. Circumstellar molecular synthesis is therefore extremely efficient (Kwok 2004).

It is interesting to note that these spectral characteristics resemble the infrared spectra seen in coal (Guillois et al. 1996), kerogen (Papoular 2001), soot (Pino et al. 2008), and petroleum (Cataldo et al. 2004). What all these compounds have in common is that they are all disorganized organic matter with mixed sp^2/sp^3 structures. While coal, kerogen and petroleum are remnants of life on Earth, the carbonaceous grains produced by stars condensed directly from the gas phase (similar to the formation process of soot) and are probably amorphous nanoparticles with a few aromatic islands connected by aliphatic chains (Kwok and Zhang 2011).

Connection with the Solar System

Laboratory analysis of meteorites and interplanetary dust particles (IDP) collected in the upper atmospheres shows signatures of complex organics. The $3.4\ \mu\text{m}$ features seen in proto-planetary nebulae are detected in IDPs (Flynn et al. 2003; Keller et al. 2004). The insoluble organic matter (IOM) in carbonaceous chondrite meteorites is found to have a structure similar to that of kerogen (Derenne and Robert 2010). Instead of being “dirty snowballs”, the nuclei of comets are believed to contain significant amounts of organics (Sandford et al. 2006; Cody et al. 2011). The colors of asteroids give indications of the presence of organics (Cruikshank et al. 1998) and these can be confirmed by future sample return missions. Even the Titan haze shows the $3.4\ \mu\text{m}$ features similar to those seen in proto-planetary nebulae (Kim et al. 2011). Recent analysis of circumstellar and interstellar spectra has shown that there is a strong aliphatic component and the carrier is more consistent with a mixed aromatic/aliphatic compound similar in chemical composition to the IOM (Kwok and Zhang 2011). A schematic of the chemical structure is shown in Fig. 2.

The similarity in chemical structure between stellar and Solar System organics suggests there may be a connection. We know that planetary nebulae eject a large amount of dust and gas into the interstellar medium, and a fraction of the ejected materials is in the form of complex organics. The typical mass loss rate per planetary nebula is $\sim 10^{-5}\ M_{\odot}\ \text{yr}^{-1}$. Assuming a dust-to-gas ratio of 0.003, the ejection rate of dust is $2 \times 10^{15}\ \text{kg}\ \text{s}^{-1}$. The birth rate of planetary nebulae in the Galaxy is $\sim 1\ \text{yr}^{-1}$, with a lifetime of $\sim 20,000\ \text{yr}$, giving about $\sim 20,000$ planetary nebulae in the Galaxy at any one time. Since about half of this number is carbon-rich, the total carbonaceous dust production rate of $2 \times 10^{19}\ \text{kg}\ \text{s}^{-1}$. Over the $10^{10}\ \text{yr}$ lifetime of the Galaxy, about $6 \times 10^{36}\ \text{kg}$ of carbonaceous solid particles has been distributed over the Galaxy. The total amount of organics delivered to Earth externally has been estimated to be 10^{16} – $10^{18}\ \text{kg}$ (Chyba and Sagan 1992), which is much larger than the total amount of organic carbon in the biosphere ($2 \times 10^{15}\ \text{kg}$, Falkowski et al. 2000). The total amount of organic carbon stored in the forms of coal and oil is more difficult to estimate. Extrapolating from existing reserves, the potential total reserve can be as high as $4 \times 10^{15}\ \text{kg}$. If we include kerogen, the total amount of organic matter in Earth is $\sim 1.5 \times 10^{19}\ \text{kg}$ (Falkowski et al. 2000).

Although a significant amount of organics were produced by stars, it is less clear how much of the ejected material was accreted into the solar nebula, or how much of this primordial organic matter has ended up on Earth. It was commonly believed that any interstellar organics in the pre-solar nebula would have been totally destroyed and re-processed during the formation of the Solar System. However, if the pre-solar organics are in the form of amorphous solids rather than gas-phase molecules, it is more likely for these

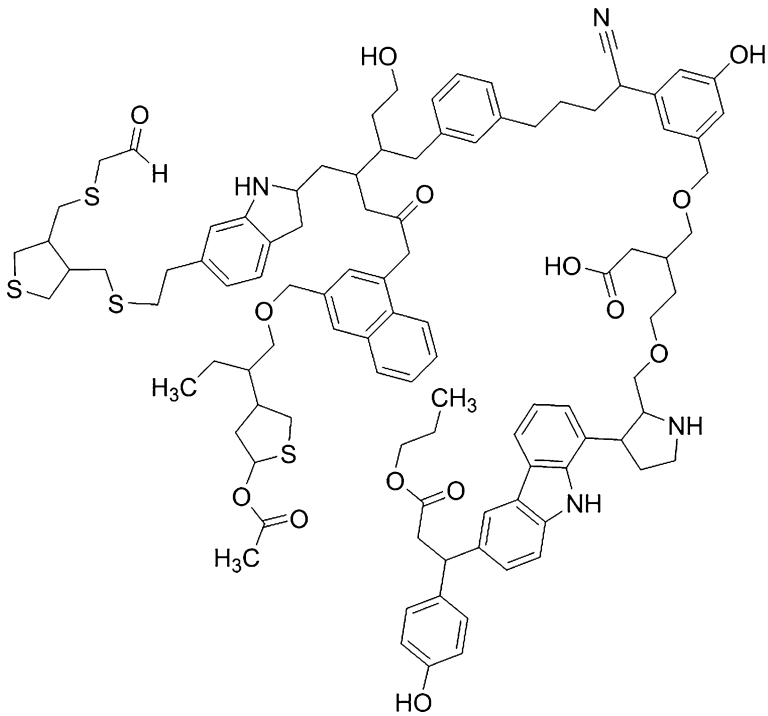


Fig. 2 A schematic of the possible structure of stellar organics. This structure is characterized by a highly disorganized arrangement of small units of aromatic rings linked by aliphatic chains. Other impurities such as O, N, and S are commonly present. This structure contains about 100 C atoms and a typical particle may consist of multiple structures similar to this one (diagram from Kwok and Zhang 2011)

complex organics to have survived and be embedded into comets, asteroids, and planetesimals. The discovery of pre-solar grains based on isotopic anomalies has confirmed that stellar grains such as silicon carbide (Bernatowicz et al. 1987), diamonds (Lewis et al. 1987), and refractory oxides (Nittler et al. 1997) can be incorporated into meteorites. The early Earth could have been chemically enriched with organic compounds through external bombardments by comets and asteroids containing these stellar materials, or even inherit the organics through the accretion process of planet formation. With our new understanding of stellar organics, may be it is time for us to reexamine the premise whether the early Solar System was completely homogenized by thermal processing.

Conclusions

There is now strong spectroscopic evidence that complex organics are being synthesized by old stars in large quantities. The discovery of pre-solar grains in meteorites shows that stellar grains can travel across the Galaxy and reach the Solar System, establishing the stellar-Solar System connection (Zinner 1998). If the early Earth was indeed enriched by stellar organics, then life may have been much easier to get started given the rich ingredients available. Instead of having to start from scratch, the aromatic and aliphatic components of these grains can serve as building blocks for nucleic acids and lipids.

On the Galactic scale, since planetary nebulae are distributed all over the Galaxy, stellar organics can easily be delivered to other planetary systems in the Galaxy. From this perspective, the availability of basic ingredients for life is not restricted to Earth and is universal over the Galaxy.

Acknowledgements I thank Anisia Tang for technical assistance. The work was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU 7027/11P).

Open Access This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- Bernatowicz T et al (1987) Evidence for interstellar SiC in the Murray carbonaceous meteorite. *Nature* 330:728–730
- Cataldo F, Keheyan Y, Heymann D (2004) Complex organic matter in space: about the chemical composition of carriers of the Unidentified Infrared Bands (UIBs) and protoplanetary emission spectra recorded from certain astrophysical objects. *Orig Life Evol Biosph* 34:13–24
- Cernicharo J et al (2001) Infrared space observatory's discovery of C₄H₂, C₆H₂, and Benzene in CRL 618. *Astrophys J* 546:L123–L126
- Chyba C, Sagan C (1992) Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: an inventory for the origins of life. *Nature* 355:125–132
- Cruikshank DP et al (1998) The composition of centaur 5145 pholus. *Icarus* 135:389–407
- Cody GD et al (2011) Establishing a molecular relationship between chondritic and cometary organic solids. *Proc Natl Acad Sci*. doi:10.1073/pnas.1015913108
- Derenne S, Robert F (2010) Model of molecular structure of the insoluble organic matter isolated from Murchison meteorite. *Meteoritics Planet Sci* 45:1461–1475
- Ehrenfreund P, Charnley SB (2000) Organic molecules in the interstellar medium, comets and meteorites: a voyage from dark clouds to the early Earth. *Ann Rev Astron Astrophys* 38:427–483
- Falkowski P et al (2000) The global carbon cycle: a test of our knowledge of earth as a system. *Science* 290:291–296
- Flynn GJ, Keller LP, Feser M, Wirick S, Jacobsen C (2003) The origin of organic matter in the solar system: evidence from the interplanetary dust particles. *Geochim Cosmochim Acta* 67:4791–4806
- Guillois O, Nenner I, Papoular R, Reynaud C (1996) Coal models for the infrared emission spectra of protoplanetary nebulae. *Astrophys J* 464:810–817
- Keller LP et al (2004) The nature of molecular cloud material in interplanetary dust. *Geochim Cosmochim Acta* 68:2577–2589
- Kim SJ et al (2011) Retrieval and tentative identification of the 3 μm spectral feature in Titan's haze. *Planet Space Sci* 59:699–704
- Kwok S (2000) Origin and evolution of planetary nebulae. Cambridge University Press
- Kwok S (2004) The synthesis of organic and inorganic compounds in evolved stars. *Nature* 430:985–991
- Kwok S (2007) *Physics and Chemistry of the Interstellar Medium*. University Science Books
- Kwok S (2011) *Organic Matter in the Universe*. Wiley.
- Kwok S, Zhang Y (2011) Mixed aromatic/aliphatic organic nanoparticles as carriers of unidentified infrared emission features, *Nature*, 479:80–83
- Kwok S, Volk K, Hrivnak BJ (1999) Chemical evolution of carbonaceous materials in the last stages of stellar evolution. *Astron Astrophys* 350:L35–L38
- Kwok S, Volk K, Bernath P (2001) On the origin of infrared plateau features in proto-planetary nebulae. *Astrophys J* 554:L87–L90
- Lewis RS, Ming T, Wacker JF, Anders E, Steel E (1987) Interstellar diamonds in meteorites. *Nature* 326:160–162
- Nittler LR, Alexander CMO, Gao X, Walker RM, Zinner E (1997) Stellar sapphires: the properties and origins of presolar Al₂O₃ in meteorites. *Astrophys J* 483:475–495

- Olofsson H (1997) The neutral envelopes around age and post-AGB objects. In: IAU Symp. 178: molecules in astrophysics probes and processes (vanDishoeck EF ed) Kluwer, pp 457–468
- Papoular R (2001) The use of kerogen data in understanding the properties and evolution of interstellar carbonaceous dust. *Astron Astrophys* 378:597–607
- Pino T et al (2008) The 6.2 μm band position in laboratory and astrophysical spectra: a tracer of the aliphatic to aromatic evolution of interstellar carbonaceous dust. *Astron Astrophys* 490:665–672
- Sandford SA et al (2006) Organics captured from comet 81P/Wild 2 by the Stardust spacecraft. *Science* 314:1720–1724
- Volk K, Xiong G-Z, Kwok S (2000) Infrared space observatory spectroscopy of extreme carbon stars. *Astrophys J* 530:408–417
- Zinner E (1998) Stellar nucleosynthesis and the isotopic composition of presolar grains from primitive meteorites. *Ann Rev Earth Planet Sci* 26:147–188