Invited Articles

外來因素對早期地球演化的影響

郭新
香港大學理學院

Extraterrestrial Influence on the Evolution of the Early Earth

Sun Kwok
Faculty of Science
University of Hong Kong
Hong Kong

Abstract

After the formation of the solid Earth through accretion 4.6 billion years ago, the atmosphere and oceans of Earth have undergone significant alterations as the result of impacts by comets and asteroids during the heavy bombardment period. Isotopic and chemical analysis of meteorites, interplanetary dust particles, and even comets have now indicated a strong stellar-solar system connection and there is evidence that stellar-synthesized inorganic and organic compounds have been delivered to the solar system.

1. Introduction

Although we generally think of the Earth as a solid, it fact it contains an atmosphere, oceans, and a biosphere. While the core, mantle, and crust of the Earth is made up of heavy elements in solid or liquid form, its atmosphere is a mixture of molecular gases (N_2, O_2, CO_2, H_2O, etc.), and the oceans are primarily H_2O in liquid form. Earth has a companion in the form of the Moon, which was created by a grazing collision with the Earth by a Mars-size proto-planet 4.53 billion years ago. The gravitational effects of the Moon cause tides in our oceans, and exerts a torque that leads to a steady lengthening of the day at a rate of 1.4 ms per century.

Furthermore, Earth is part of the solar system with the Sun as the dominant body. The Earth shares this space with other planets, asteroids, comets, and outer solar system bodies such as Kuiper Belt Objects. Radiation input from the Sun keeps the Earth at a relatively warm temperature (~300 K), and provides energy for photosynthesis. The gravitational pull from the Sun drives the Earth in an orbital motion that gives us seasonal variations. Particles in the form of solar wind interact with the Earth's magnetic field, creating the magnetosphere and visible phenomena such as auroras. It is also possible that the major glaciation episodes are related to the orbital and spin variations of the Earth, including precession and the change in eccentricity of orbit due to planetary tidal pulls.

The first condensate of the solar system is chondrites, which took place 4.567±0.002 billion years ago. The present day planets are the products of collisional accretion of primitive planetismals of size between 10 and 1000 km. It is clear that both in the past and present, the Earth is under extensive radiative, gravitational, and mechanical interactions with our neighbors.

2. Earth is not an isolated body

The fact that the Earth, the Moon, Mercury and Mars are full of craters from past collisions with asteroids and comets is evidence that the Earth is not a closed system. During the first 800 million years, the Earth was subject to heavy bombardments from asteroid and comets, which continue at a reduced rate even to this day.

Although the oceans have an average thickness of 3.7 km (which corresponds to 0.06% of the thickness of the Earth), they cover 71% of the Earth's surface area. The total mass in the oceans is however small: 1.4×10^{21} kg, or 0.02% of the Earth's total mass. Water, in its three phases: liquid ocean, solid ice caps, and water vapor in the atmosphere, play an important role in the radiative balance of the Earth and serve as a medium for the origin of life. The origin of water on Earth, however, is not an easy question to answer. Geologists believe that water was trapped in minerals that formed the Earth and later outgassed by the hot mantle. Another school of thought believes that the main fraction of water on Earth was brought here by external impacts (Delsemme 1996). It is estimated that several earth masses of hydrated asteroids in the outer asteroid belt could have brought enough water to Earth to form the present oceans (Chyba 1990).

The Earth's atmosphere, although important for our existence, is very thin. It has a total mass of only 5×10^{18} kg, and if completely condensed as ices, will form a layer of only 10 m thick. We should note that this fragile atmosphere is not primordial and has undergone major evolution through Earth's history. The primary atmosphere consisting of H, He, CH_4, NH_3, and H_2O is almost totally gone due to evaporation, replaced by a secondary atmosphere consists of H_2O, CH_4, CO_2, SO_2, etc, due to outgassing from the interior. Volatiles imported by comets and meteorites may have also contributed to this secondary atmosphere. The most dramatic change in our atmosphere occurred 3.5 billion years ago with the introduction of O_2 and O_3 after life began to spread on Earth. Biogenic production of O_2 by photosynthesizing microbes and the rise in oxygen in the atmosphere led to the diversification of eukaryotic cell and subsequent biological evolution on Earth (Ehrenfreund et al. 2004).

3. Exogenous delivery to Earth

Comets have always been considered as a possible source of extraterrestrial materials to Earth (Oró, 1961; Hoyle and Wickramasinghe 1999). Modern remote spectroscopic observations as well as in-situ measurements have greatly improved our understanding of the physical and chemical structures of comets. The outgassing of molecules can be observed by mm/submm spectroscopy and the solid-state component of comets can be analyzed through infrared spectroscopy. The sublimation of organic compounds and release of polymers have been detected through mass spectrometry. The return of the samples from Comet Wild 2 through the STARDUST mission is a major step to have a complete picture of the chemical constitution of comets (Sandford et al. 2006).

In addition to the H_2O, CO_2, and other ices made up of C, N, and O, comets also contain inorganic minerals from rock-forming elements such as Mg, Si, Ca, Fe, etc. Furthermore, comets have an organic refractory material component made up of H, C, O, and N. In other words, comets as we know them today are much more than just “dirty snow balls” (Fernández 2005).

Even asteroids, which we used to think of as just large (10-1000 km) chunks of rocks, are now found to contain amino acids and other complex organic molecules. Analysis of meteorites has shown that they are rich in organic compounds. Hydrocarbons, alcohols, carboxylic acids, amines, amides, uracil, adenine, quinine, and over 70 amino acids have been identified in carbonaceous meteorites (Cronin and Chang 1993, Nakamura-Messenger et al. 2006).

Besides comets, asteroids, and meteorites, micrometeorites are also capable of importing extraterrestrial materials to Earth. They mostly float onto Earth non-destructively and therefore are good molecule carriers. The rate of micrometeorites infall is estimated as 20,000 tons per year. Assuming the 80% of these micrometeorites are carbonaceous and each containing 2% carbon, 320 tons of carbonaceous matter will arrive on Earth every year. Since the total amount of organic carbon in the biosphere is $\sim 10^{12}$ ton, 3 Gyr will be needed to accrete this amount. Since the accretion rate was 100 times higher 4 Gyr ago, only 30 Myr was needed to accumulate all the carbonaceous ingredients for life.

4. Star dust in the solar system

In recent years, it is increasingly recognized stars in the late stages of evolution are proficient molecular factories and are a major sources of inorganic and organic molecules and solid-state compounds in the Galaxy. Microwave and infrared spectroscopy has identified over 60 molecules through their rotational and vibrational transitions. Solid-state grains including amorphous and crystalline silicates, silicon carbide, and various kinds of refractory oxides (corundum, spinels, rutile, etc.) have been identified through their lattice vibrations. These molecules are grains are formed in the circumstellar environment of asymptotic giant branch (AGB) stars and ejected to the interstellar medium through their strong stellar winds.

Isotopic analysis of meteoritic materials has led to the conclusion that grains of pre-solar origin are present in the solar system, and these grains have their origin in AGB stars (Bernatowicz and Zinner 1997). The stellar grains identified include nanodiamonds, graphite, silicon carbide, corundum, spinel, etc. (Zinner 1998, Nittler et al. 1997). Spectroscopic observations of comets have shown that they possess amorphous and crystalline silicates similar to those produced by AGB stars. Silicates of stellar origin are also now detected in meteorites (Nguyen and Zinner 2004). The establishment of this stellar-solar system connection has greatly enhanced interests in exogenous delivery as a mechanism of chemical enrichment of the early Earth.

The AGB is an evolutionary stage passed through by ~95% of all stars. After the AGB, the stars will evolve to go through the proto-planetary nebulae stage to become a planetary nebula (Kwok 2000). During the proto-planetary nebulae phase of evolution, signatures of compounds of aliphatic and aromatic structures begin to emerge (Kwok et al. 2001). By the time the star evolves to the planetary nebulae stage, the aromatic features become very strong (Figure 1-3).

The exact chemical structures of these carbonaceous compounds are not clear. They most likely consist of a combination of aliphatic and aromatic groups, not unlike the structure of kerogen or coal (Papoular et al. 1989, 1996; Guillois et al. 1996, Pendleton and Allamandola, 2002). Other possibilities include polycyclic aromatic hydrocarbons (Allamandola et al. 1989), or artificial substances not found in the natural terrestrial environment, e.g., hydrogenated amorphous carbon and quenched carbonaceous composites (Jones et al. 1990, Sakata et al. 1984). No matter what the substance is, it is clear that stars are capable of synthesizing extremely complex organic materials under very low density conditions, over very short (several hundred to several thousand years) time scales, and spreading such products widely throughout the Galaxy (Kwok 2004).

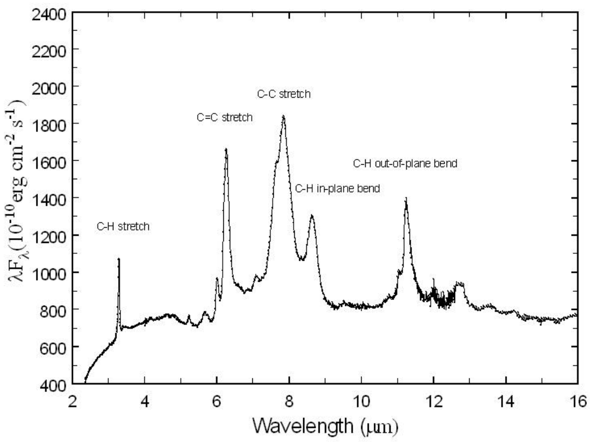

Fig 1: The *ISO SWS* spectrum of HD 44179 (the Red Rectangle) showing strong emission features due to the stretching and bending modes of aromatic compounds.

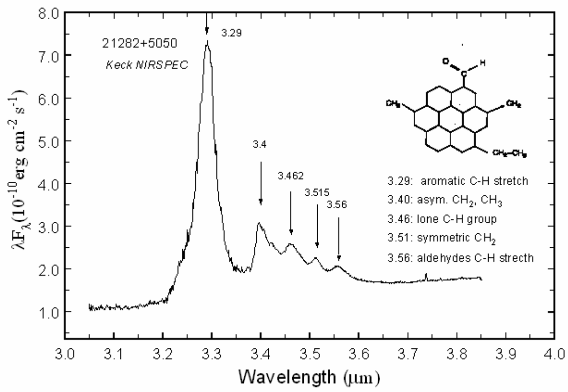

Fig 2: The spectrum of IRAS 21282+5050 showing the stretching modes of CH_2 and CH_3 sidegroups, as well as the 3.56 μm feature due to aldehydes

5. Conclusions

We now appreciate that the early evolution of the Earth was not just influenced by radiative, gravitational, and mechanical interactions with external sources, it was also very likely to have been chemically enriched during the early days of the solar system. Complex organic molecules and solids are constantly being manufactured in stars and ejected in the interstellar medium. While some may have been destroyed during this journey, there is strong evidence that some have survived and reached our solar system. The journey through the Galaxy is not totally destructive, however. Laboratory simulations have shown that chemical reaction on grain surfaces under exposure to interstellar ultraviolet radiation can synthesize amino acides, diaminopentanoic acid, diaminohexanoic acid, and nucleic acd bases (Bernstein et al. 2002; Muňoz Caro et al, 2002). To what extent these stellar and interstellar materials contribute to the origin of life on Earth is an exciting scientific question to answer in the coming decades (Ehrenfreund et al. 2002).

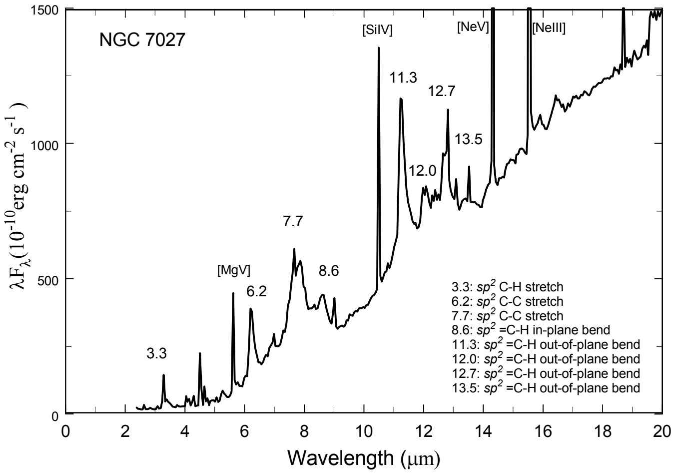

Fig. 3: The *ISO SWS* spectrum of the planetary nebula NGC 7027 is dominated by a strong dust continuum (peaking at ~30 μm), and atomic emission lines due to fine-structure transitions of heavy elements (e.g., the [Ne III] line at 15.6 μm). The aromatic features are marked by their peak wavelengths and their identification is listed in the legend.

Acknowledgements

I would like to thank the Chinese Astronomical Society (Taipei) for inviting me to give this lecture at their general meeting in June, 2007. My work is supported in part by the Natural Science and Engineering Research Council of Canada, and in part by the Research Grants Council of Hong Kong.

References

Allamandola, L.J., Tielens, A.G.G.M. and Barker, J.R. 1989, Interstellar polycyclic aromatic hydrocarbons - the infrared emission bands, the excitation/emission mechanism, and the astrophysical implications, *ApJS*, 71, 733.

Bernatowicz, T.J., Zinner, E. 1997, *Astrophysical Implications of the Laboratory Study of Presolar Materials*, American Institute of Physics (New York).

Bernstein, M.P., Dworkin, J.P., Sandford, S.A., Cooper, G.W., Allamandola, L.J. 2002, reemic Amino Acids from the Ultraviolet Photolysis of Interstellar Ice Analogues, *Nature*, 416, 401.

Cronin, J.R., and Chang, S. 1993, *The Chemistry of Life's Origin*, ed. J.M. Greenberg, X.X. Mndoza-Gomez and V. Pirronello, (Dordrecht: Kluwer), p.209

Chyba, C.F. 1990, Impact delivery and erosion of planetary oceans in the early inner Solar System, *Nature*, 343, 129.

Delsemme, A. 1996, *The origin of the atmosphere and of the oceans, Comets and the Origin and Evolution of Life*, eds. P.J. Thomas, C.F. Chyba, C.P. McKay, Springer, p.29.

Ehrenfreund, P. et al. 2004, *Astrobiology: future perspectives*, Kluwer.

Ehrenfreund, P. et al. 2002, Astrophysical and Astrochemical Insights into the Origin of Life, *Rep. Prog. Phys.*, 65, 1427.

Fernández, J.A. 2005, *Comets: nature, dynamics, origin, and their cosmognoical relevance*, Spinger.

Guillois, O., Nenner, I., Papoular, R., and Reynaud, C. 1999: Coal Models for the Infrared Emission Spectra of Proto-Planetary Nebulae, *ApJ*, 464, 810.

Hoyle, F., Wickramasinghe, N.C. 1999, Comets - a vehicle for panspermia, *Astrophys. Sp. Sc.*, 268, 333.

Jones, A.P., Duley, W.W. and Williams, D.A. 1990, The structure and evolution of hydrogenated amorphous carbon grains and mantles in the interstellar medium. *Q. J. R. Astron. Soc.*, 31, 567.

Kwok, S. 2004, The Synthesis of Organic and Inorganic Compounds in Evolved Stars, *Nature*, 430, 985.

Kwok, S. 2000, *Origin and Evolution of Planetary Nebulae*, Cambridge University Press.

Kwok, S., Volk, K., and Bernath, P. 2001: On the Origin of Infrared Plateau Features in Proto-Planetary Nebulae, *ApJL*, 554, L87.

Muňoz Caro, G.M., et al, 2002, Amino Acids from Ultraviolet Irradiation of Interstellar Ice Analogues, *Nature*, 416, 403.

Nakamura-Messenger, K., Messenger, S., Keller, L.P., Clemett, S.J., Zolensky, M.E. 2006, Organic globules in the Tagish Lake Meteorite: remnants of the protosolar disk, *Science*, 314, 1439.

Nguyen, A.N., and Zinner, E. 2004, Discovery of ancient silicate stardust in a meteorite, *Science*, 303, 1496.

Nittler, L.R., O'D. Alexander, C.M., Gzo, X., Walker, R.M., and Zinner, E. 1997, Stellar sapphires: the properties and origins of pre-solar Al_2O_3 in meteorites, *ApJ*, 483, 475.

Oró, J. 1961, Comets and the formation of bio-chemical compounds on the primitive Earth, *Nature*, 190, 389.

Papoular, R., Conard, J., Giuliano, M., Kister, J. and Mille, G. 1989, A coal model for the carriers of the unidentified IR bands, *A&A*, 217, 204.

Papoular, R., Conard, J., Guillois, O., Nenner, I., Reynaud, C. and Rouzaud, J.-N. 1996, A comparison of solid-state carbonaceous models of cosmic dust, *A&A*, 315, 222.

Pendleton, Y.J. and Allamandola, L.J. 2002, The organic refractory material in the diffuse interstellar medium: mid-infrared spectro-scopic constraints, *ApJS*, 138, 75.

Sandford, S. et al. 2006, Organics Captured from Comet 81P/Wild 2 by the Stardust Spacecraft, *Science*, 314, 1720.

Sakata, A., Wada, A., Tanab'e, T. and Onaka, T. 1984, Infrared spectrum of the laboratory-synthesized quenched carbonaceous compo-site (QCC): comparison with the infrared unidentified emission bands, *ApJL*, 287, L51.

Zinner, E. 1998, Stellar nucleosynthesis and the isotopic composition of presolar grains from primitive meteorites. *Ann. Rev. Earth Planet. Sci.*, 26, 147.