From "Frontiers of Astronomy" to Astrobiology

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Abstract

In his book *Frontiers of Astronomy,* Fred Hoyle outlined a number of ideas on the stellar synthesis of solid-state materials and their ejection into the interstellar medium. He also considered the possibility of interstellar organics being integrated into the early Earth during the accretion phase of planetary formation. These organics may have played a role in the origin of life and the creation of fossil fuels. In this paper, we assess these ideas with modern observational evidence, in particular on the evidence of stellar synthesis of complex organics and their delivery to the early Solar System.

Key words: interstellar molecules – planetary atmospheres – Solar System – stellar evolution – astrochemistry – astrobiology

I. Introduction

Frontier of Astronomy (Hoyle, 1955) is a remarkable book. It was the first popular book to introduce modern astrophysics, specifically the application of atomic and nuclear physics to astronomy, to the non specialist. I know many professional astronomers (me included) who went into the field after reading this book. Hoyle showed that modern physics is relevant to, and is necessary to comprehend, many different cosmic phenomena. The book also covers a wide range of topics, from the Earth, the Moon, planets, and comets, to stars, interstellar medium, galaxies, and cosmology. By touching upon astronomy, biology, chemistry, geology, physics, and planetary science, Hoyle has also elevated astronomy from a classical, observational subject to a modern, interdisciplinary endeavor.

The most amazing thing is that 55 years after this book was written, it still feels surprisingly modern. The reason is that on many topics, Hoyle was ahead of his time, as clearly demonstrated by one of his biographers (Mitton, 2011). He may not have had all the evidence to support his theories, but he had many of the essential ideas correct, often decades before others. In 1955, the disciplines of astrochemistry and astrobiology had not yet been established (they began in the 1970s and 1990s, respectively), but parts of Holye's book already foresaw the development of these fields. In this paper, I will cite some examples relevant to these topics, in particular the effects of stellar synthesis of organics on the Solar System.

II. Star dust in the making

The existence of interstellar dust (micron-sized solid-state particles) has been known since the early 20th century. However, the origin of the dust is not known. The possibility that dust condensed in the atmospheres of evolved stars and was ejected into the interstellar medium was suggested by Hoyle:

> ”Dust particles originate in the atmosphere of stars of low surface temperature. It can be shown that at temperatures below about 2,000 degrees, carbon atoms in the atmosphere of a star will not remain gaseous but will condense into solid particles. It can also be shown that when the particles grow to about the wavelength of blue light – about one-hundred-thousandth of an inch – the radiation from the star pushes them outwards even in spite of the inward gravitational pull of the star” (Hoyle 1955, p. 240).

The condensation of solids in stellar atmospheres is not obvious. The gas density in the extended red giant atmospheres is very low. If we rely on traditional collisional nucleation processes under thermodynamical equilibrium conditions, such condensation is theoretically almost impossible. With the development of mid-infrared spectroscopy in the late 1960s, circumstellar grains were detected through their thermal emission. Large excesses of mid-infrared radiation above the level of stellar photospheric continuum emission were commonly found in red giant stars, showing that these stars can produce grains extremely efficiently (Woolf & Ney, 1969). Although we do not understand theoretically how they occur, observations have shown that stars can make large quantities of solids with no difficulty.

The explicit mechanism of ejection of the grains suggested by Hoyle is radiation pressure. From the extinction coefficient of the particles and the luminosity of the stars, the ejection velocity can be estimated to be of the order of 1000 km s^{-1} (Hoyle & Wickramasinghe, 1962). From the large infrared excesses observed, we know that the dust density in the circumstellar envelopes is high, and the grains cannot be moving at speeds of thousands of km s^{-1} as this velocity would mean that the dust density would thin out very quickly. The solution was that the dust grains are slowed down by gas drag, where dust-gas collisions and gas-gas collisions effectively transfer the momentum the dust to the gas (Kwok, 1975). Since there is a lot more gas than dust, the dust grains are slowed down from 1000 km s^{-1} to a few tenths of km s^{-1}, and the gas is accelerated to almost the same velocity. This transfer of momentum from the dust to the gas causes a large fraction of the stellar mass to be lost in the form of a stellar wind. This loss of mass has significant effects on the evolution of an intermediate-mass (1-8 $M_{\odot}$) star, preventing it from igniting carbon in the core and becoming a supernova (Kwok, 1987). The major components of this wind are molecular gases, which manifest themselves through their rotational transitions. With the advance in millimeter-wave spectroscopy in the early 1970s, the expansion of the molecular gas can be measured directly from their emission line profiles and their velocities are found to be in the range of 10-20 km s^{-1} (Kuiper et al., 1976).

Since the first detection of CO in the red giant IRC+10216 in 1970 (Solomon et al., 1971), over 60 molecular species have been detected in the circumstellar envelopes of evolved stars. The detected molecular species include inorganics (CO, SiO, SiS, NH_3, AlCl), organics (C_2H_2, CH_4, H_2CO, CH_3CN), radicals (CN, C_2H, C_3, HCO^+), cyclic molecules (C_3H_2), and cyanopolyynes (HCN, HC_3N, ... HC_9N). From infrared spectroscopy, in particular from space-based telescopes such as *Infrared Astronomical Satellite*, *Infrared Space Observatory*, and the *Spitzter Space Telescope*, many different kinds of amorphous and crystalline solids have been observed. The most common kind of dust in oxygen-rich stars is amorphous silicates, and in carbon-rich stars silicon carbide (Kwok et al., 1997). These results show that evolved stars are molecular factories capable of producing a large variety of molecules and solids and ejecting them in large quantities into the interstellar medium.

Most interestingly, stars in the late stages of stellar evolution are found to produce grains of complex aromatic and aliphatic structures. By following the spectral evolution of stars on the asymptotic giant branch (AGB), proto-planetary nebulae (PPN), and planetary nebulae (PN), we can actually witnessed the formation of complex organic compounds in the very low-density circumstellar environment over time scales as short as 10^3 yr (Kwok 2004).

As one of the pioneers in the field of stellar nucleosynthesis, Hoyle was no doubt aware of the significance of the nucleosynthesis of the element carbon in the late stages of stellar evolution, and the possibility of this element serving as basic ingredients for the synthesis of carbon-based molecules and solids in the stellar atmosphere. In *Frontiers of Astronomy*, Hoyle foresaw the condensation of dust particles in the atmospheres of cool stars under near-vacuum conditions and their ejection into the interstellar medium. His interest in carbon as an ingredient of these grains also suggests the role of evolved stars in the chemical enrichment of the Galaxy. This is significant because at the time of his writing, the existence of circumstellar grains was not known, and no one has given any thought to the possibility of evolved stars being a major source of organic molecules and solids in the Galaxy.

III. Organic star dust in the primordial Earth

The connection between evolved stars and the Solar System was firmly established with the discovery of pre-solar grains. Isotopic studies of meteorites have identified SiC (Bernatowicz et al. 1987), diamonds (Lewis et al. 1987), conrumdum (Nittler et al. 1997), spinals, and other solid grains as being of stellar origin (Zinner 1998). The silicate features, both amorphous and crystalline, have been detected in comets (Wooden et al., 1999), interplanetary dust particles (IDP, Messenger et al. 2003), and meteorites (Nguyen et al., 2004). The aliphatic C–H vibrational stretch features at 3.4 µm, similar to those observed in PPNs, have been detected in meteorites (Pendleton et al. 2002), comets (Davies et al. 1993), and IDPs (Clemett et al. 1993).

In spite of the common perception that Solar System objects consist primarily of metals, minerals, and ices, complex organics are in fact widely present in the Solar System. Laboratory analyses of carbonaceous meteorites have shown that the majority of organic matter in these objects is in the form of insoluble macromolecular organic matter (IOM). Gas chromatography has characterized IOM as predominantly aromatic with aliphatic functional groups (Kerridge 1999). X-ray absorption near-edge spectroscopy of IDP has revealed similar structures in IDPs (Flynn et al. 2003). Rather than being just “dirty snow balls”, comets are now found to have organic refractory materials consisting of H, C, N,and O in the nucleus. Samples of Comet Wild 2 returned by the STARDUST mission have also found organic contents similar to IOM (Sandford et al. 2006). Although there are no good spectroscopic observations or sample return from asteroids, the red colors of asteroids are also suggestive of organic substance on the surface (Cruikshank et al. 1998). In planetary satellites, the Cassini-Huygens mission has found N-rich amorphous carbonaceous compounds (generally referred to as tholins-like materials by the space science community) in the atmosphere and on the surface of Titan (Nguyen et al. 2007). The amount of carbon in the form of methane in the Titan atmosphere is estimated to be 360,000 giga tons (Gt), while the amount of carbon in liquid form (ethane and methane) in lakes is 16,000-160,000 Gt. However, the greatest amount is in organic solids contained in sand dunes, with an inventory of 160,000-640,000 Gt (Lorenz et al. 2008). This is much larger than the total sum of organics on Earth. Apparently, Titan accumulated a lot of organics without the benefit of having them generated by living matter.

If the early Solar System inherited a lot of stellar/interstellar organics, could any of these organics be incorporated into the primordial Earth? On this question, Hoyle has the following to say:

> “An interplanetary origin of life would have seemed impossible in the days when it was believed that the Earth was formed in an entirely molten state, for the associated high temperature would have destroyed all complex organic molecules. Now that we realize that the Earth must have accumulated from a multitude of cold bodies it is no longer possible to be sure of this. It is true that the temperature deep inside the Earth became high due to compression, but the temperature at, and near the surface probably was quite low especially during the last phases of the

> aggregation process. I do not see why already complicated chemical structures should not have been added to the Earth in this phase". (Hoyle 1955, p. 103).

This paragraph clearly outlines Hoyle's belief that complex organics could be present in the interior regions of primordial Earth. We now know that stars can manufacture large quantities of complex organics near the end of their lives. These organics are ejected into the interstellar medium at rapid rates and are incorporated into molecular clouds, the parent bodies of star formation. These organics are preserved in meteorites, comets, and IDPs. We also know that these organics were delivered to the early Earth by external bombardments. What we do not know is: what is the quantity of pre-solar organics embedded in the primordial Earth? If significant quantities were inherited, what are the implications for the development of life on Earth?

IV. The existence of primordial hydrocarbons

One of the greatest surprises of modern astrochemistry is that evolved stars are capable of synthesizing complex organic solids with aromatic and aliphatic structures (Kwok 2004). Observations of AGB stars and their descendents PPNe and PNe have revealed the gradual formation of diacetylene (C_4H_2), triacetylene (C_6H_2), and benzene (C_6H_6) (Cernicharo et al. 2001). Emission features arising from the stretching and bending modes of aromatic (at 3.3, 6.2, 7.7, 8.6, 11.3 µm, collectively known as the aromatic infrared bands, or AIB) and aliphatic (3.4 and 6.9 µm) structures also emerge during this phase. The infrared spectra of PPNe display broad emission plateaus at 8 and 12 µm, which originate from a collection of different in-plane and out-of-plane bending modes of aliphatic groups attached to aromatic rings (Kwok et al. 2001). There is evidence of the chemical structure becoming more aromatic as the star evolves from PPNe to PNe, probably as the result of photochemistry. The combination of the AIBs and emission plateaus suggests that the carrier is a kerogen-like organic solid (Guillois et al. 1996). The chemical structure of kerogen is represented by random arrays of aromatic rings linked by long, aliphatic chains and its infrared spectrum is characterized by C–H stretches of the methyl and methylene groups at 3.4 µm, strong plateaus at 8 and 12 µm, and various aromatic features due to C–H and C–C stretching and bending modes (Papoular 2001).

Organic matter on Earth is dominated by products of life. The total biomass in the biosphere is about 2,000 Gt. Fossil fuels such as coal, oil, and gas, representing remnants of past living matter, add up to ~4,000 Gt. The largest amount of organic matter is actually in the form of kerogen (1.5 10^7 Gt) (Falkowski et al. 2000). Kerogen is a solid sedimentary, insoluble, organic material found in the Earth upper crust (Durand, 1980). Kerogen is mostly believed to be of biological origin, although alternate scenarios of abiological synthesis have also been proposed (De Gregorio & Sharp, 2006). Assuming the lifetime for biomass is 10^2 yr, over the life time of life on Earth (~10^9 yr), the accumulated dead biomass is ~2 10^{10} Gt, which can account for the kerogen reserve.

Together with other fossil fuels such as coal and natural gas, petroleum found on Earth is derived from the decomposition of living matter. Remnants of living matter buried under high temperature and pressure were first transformed into kerogen, which under further heating produced petroleum (Dow 1977; Helgeson et al., 2009). This theory of formation is based on the presence of biological markers although there have been alternate theories of the origin of oil (Kenney et al., 2002). The abiological theory of oil was first developed in the Soviet Union in the 1950s and remained popular there for about 30 years. The theory proposes that petroleum hydrocarbons can be synthesized by inorganic means in the Earth's mantle (Porfir'ev 1974). Under high pressure and temperatures at depths >100 km, it is possible to convert methane to complex mixtures of alkanes and alkenes. The possibility of outgassing of hydrocarbons from the mantle along deep faults has also been discussed. This theory was expanded by Thomas Gold, who suggested that oil and gas were produced from methane that migrated from the interior of the Earth (Gold, 2001). Gold based his theory on the observation that methane is abundantly present in the atmospheres of the Jovian planets and therefore primordial methane could also be available on Earth.

The biological origin of oil was questioned by Hoyle:

> "The idea that oil, so important to our modern civilization, has been squeezed out of the Earth's interior derives an immediate plausibility from Urey's discovery that the meteorites contain small concentrations of hydrocarbons. The presence of hydrocarbons in the bodies out of which the Earth is formed would certainly make the Earth's interior contain vastly more oil than could ever be produced from decayed fish – a strange theory that has been vogue for many years" (Hoyle 1955, p. 37).

In this paragraph, he speculated that primordial hydrocarbons were incorporated in the formation of the Earth, resulting in vast reservoir of oil in the deep interior of the Earth. Through laboratory analysis of meteorite samples, we now know that meteorites contain much more than hydrocarbons (Cronin et al., 1987). In the soluble component of meteorites, carboxylic acids (Shimoyama et al., 1989), amino acids (Cronin et al., 1995), aromatic hydrocarbons (Gilmour & Pillinger, 1994), heterocyclic compounds (adenine, quinine, hypoxanthine, xanthine, uracil, thymine, cytosine, etc, Stoks & Schwartz, 1981), aliphatic hydrocarbons (Cronin et al., 1990), amines, amides (Pizzarello et al., 1994), alcohols, aldehydes, ketones, and sugars (Cooper et al., 2001) have been identified. The majority of organic matter in carbonaceous meteorites is IOM, a macromolecular solid of predominantly aromatic structure with various functional groups. In a way, the IOM is very similar to kerogen on Earth.

If the Earth was formed by aggregation of planetesimals, to what extent did these extraterrestrial organics contribute to the chemical makeup of the primordial Earth? One may argue that, as adventurous as Hoyle was, maybe he did not go far enough? If stars are capable of synthesizing complex organics such as kerogen, and kerogen-like materials are found in primitive meteorites, could fossil fuels been derived directly from these complex organics rather than synthesized from simple hydrocarbons, as described in the abological theories of oil?

V. Conclusions

In his book *Frontiers of Astronomy* Fred Hoyle predicted some of the future developments in modern astrochemistry and astrobiology. Some of these predictions have been verified by new data, and others have yet to be confirmed. But there is no doubt that Hoyle had a lot of foresight and his book has been tremendously influential, both in arousing interests and forecasting future developments in the discipline of astrobiology.

Acknowledgements: The observational evidence for the presence of organics in space and the implications of these observations on the evolution of the early Solar System is discussed in detail in the book “Organic Matter in the Universe” (Kwok, 2011). This work is supported in part by a grant to SK from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. HKU 7020/08P).

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