THE ROLE OF COMETARY AND METEORITIC DELIVERY IN THE ORIGIN AND EVOLUTION OF LIFE: BIOGEOLOGICAL EVIDENCES REVISITED. Alberto G. Fairén. Centro de Biología Molecular, Universidad Autónoma de Madrid, 28049-Cantoblanco, Madrid, Spain (agfairen@cbm.uam.es).

Introduction. Is life a highly improbable event, or is it rather the inevitable consequence of the evolution of a chemically-enriched Universe? How important is interstellar chemistry to understanding the creation of biological molecules? How is the biological evolution influenced by the stochastic meteoritic delivery? These concepts are intrinsically joined, and together have determined the history of life on Earth.

The biogenic potential of the early Earth. The interstellar clouds are ubiquitous chemical reactors [1-4], where about 130 different molecules exist, formed in a low-temperature chemistry on grain ice surfaces. From such clouds the new planetary systems are formed.

1. Water. Earth’s treasure. Only after H₂ and CO, H₂O is the most abundant molecule in the star-forming regions [1]. Meteorites composition can be assumed as representative of the bulk masses of the protoplanets, as they are almost not modified due to their limited size and inner heat scarce enough to have evolved geologically. For example, CI-carbonaceous chondrites, the most primitive meteorites, contain up to 20% water; following such proportion, early Earth may have harboured great amounts of water.

2. Amino acids. The building blocks of life can spontaneously be formed in the interstellar space, as is demonstrated when analogs of the interstellar clouds where tiny grains form clouds of gas and dust are illuminated with UV radiation [5,6]. Concretely, laboratory experiments yielded the formation of 16 amino acids, 6 of them protein-forming: alanine, serine, proline, valine, glicine and aspartic acid [6]. Importantly, they are in the same optical configuration (L) as those in the living systems, probably as a result of the circular polarization of light at short wavelengths due to dust dispersion in stellar nebulae [7].

3. Lipids. The laboratory simulations of interstellar ice mixtures also yielded products with chain lengths sufficient to aggregate amphiphilic vesicle-forming compounds, in which internal structures were observed, suggesting that phase separation occurred within the droplets [8]. The species are quite similar to lipids, whose vesicular self-assembling behaviour when in hydrated environments is the biochemical basis of the cell’s membranes, universally distributed in the biosphere.

4. Sugars. Ethylene glycol (HOCH₂CH₂OH), a chemically reduced form of 8-atom glycolaldehyde, the simplest member of the sugar family, has been detected in emission in massive interstellar clouds [9]. This suggests that the synthesis of the more complex sugar Ribose, required for the backbone structure of RNA, may be occurring in space.

The second creation. Soon after the planetary accretion, many comets and asteroids contributed to enrich the atmospheres and oceans of the new planets. The joint contribution of comets, meteorites and interplanetary dust particles (IDP’s) has been estimated in 7x10²⁵ kg of material delivered over the Earth in 4500 m.y. [10], playing a key role in the origin of life.

1. Comets. The idea that comets may have formed early Earth’s oceans is old [11]. But the composition of the comets we know today, coming from the Oort’s Cloud, is clearly different than that of the water in the Earth’s oceans. Surprisingly, the analysis of the ice in the Jupiter-orbit comet LINEAR has revealed a D/H ratio identical to that in the oceans [12]; probably, comets compositionally close to LINEAR sprinkled the young planets with huge quantities of water [13]. These comets formed nearer to the Sun than those from the Oort’s cloud, and might have been much more common in the early history of the Solar System, as the majority of the protoplanetary material was concentrated near Jupiter. In them, a number of chemical reactions were activated by the light and warmth, and so they incorporated a large amount of complex organic molecules.

2. Meteorites. Most of the organic molecules in meteorites survived the atmospheric friction and the final impact, as the meteorite forms the fusion crust [14], so preserving the inner content at low temperatures. In fact, amphiphilic vesicle-forming compounds, amino acids, purines and pyrimidines have been found in meteorites, such as the Murchison carbonaceous chondrite (92 amino acids found to date) [15]. As there are only a few known prebiotic synthesis routes for lipids, and the CO₂-based Earth’s ancient atmosphere might have been able to render only traces of amino acids, the delivery of exogenous material may have been an important source of organic molecules.

3. IDP’s. The flux of unaltered organic molecules reaching the Earth’s surface as IDP’s is much greater than that coming as meteorites and comets together [16], and so delivery of intact exogenous organics in IDP’s may have
been the dominant source of prebiotic organics on the early Earth [10].

**Demons from the sky.** Soon after the formation of the Earth, a big piece of rock crashed with our planet forming the Moon [17], a big satellite which has maintained stable the rotation axis of the Earth, so stabilizing the long-term climate. But this same processes have a less charming face: the biological evolution has passed through some deep crises, some of them probably related to bolide impacts:

1. **End of Ordovician.** The Ordovician was a period of relative stability in the Paleozoic, and consequently a substantial growth in biological diversity occurred. But in the late Ordovician, generic diversity dropped to about the level of the Carboniferous, while the generic diversity of the Permian fuelled the speculation of an impact event [23]. Among the possible candidates, a nickel-rich layer [22] in sediments from the end of the Permian fuelled the speculation of an impact event causing such extinction. The massive impact converted large amounts of solid sulphur into sulphur-rich gases, that could have consumed 20-40% of the atmosphere's oxygen, and generated enough acid rain to raise the acidity of the ocean's surface waters temporarily. Alternatively, a volcanic flooding that released a million cubic kilometres of lava [23] has been proposed to explain the world's greatest mass extinction.

2. **End of Devonian.** During the late Devonian, a mass extinction killed as many as 70% of all species in the Earth. Stratigraphy comprises a sequence of 18 sea-level changes [19], and the transition from global warm to cold environmental conditions began with a first glaciation pulse in SW Gondwana. Cometary and meteoritic impacts seems to be in the origin of the climatic perturbations [20].

3. **End of Permian.** The Permian period ended with the extinction of 95% of all species. The discovery of fullerenes [21] and rocks with a nickel-rich layer [22] in sediments from the end of the Permian fuelled the speculation of an impact event causing such extinction. The massive impact converted large amounts of solid sulphur into sulphur-rich gases, that could have consumed 20-40% of the atmosphere's oxygen, and generated enough acid rain to raise the acidity of the ocean's surface waters temporarily. Alternatively, a volcanic flooding that released a million cubic kilometres of lava [23] has been proposed to explain the world's greatest mass extinction.

4. **End of Triassic.** The rise of the giant Jurassic dinosaurs may be also linked to a meteoritic collision [24], likely in the form of a multiple impact event [25]. The effects of the impacts killed off or reduced many competitive species, paving the way for dinosaurs to adapt. After the Triassic-Jurassic boundary, herbivores dwindled and large carnivorous theropod dinosaurs flourished. Simultaneously, spores of ferns, the first plants to colonize devastated areas, also rise dramatically.

5. **End of Cretaceous.** It has been long recognized the Limit K/T as a benchmark in the history of life, marking a sharp transition between two entirely different assemblages of animals and plants. An impact of a 10-km-diameter comet or asteroid, around 65 million years ago, was firstly identified with the large, buried crater of Chicxulub ("demons’s tail", in the mayan language), on the Yucatan Peninsula of Mexico [26]. A fragment of the impactor has been recently recovered [27]. High-scale volcanism has also been proposed to explain the mass extinction at the K/T boundary [28].

**Perspectives.** Comets and meteorites can sow the seeds of life in a planetary surface, but can also reduce a complete biosphere to debris. And the process seems to be not exclusive of the Solar System: KH15D Monoceros, a very young solar-type star, is hidden 18 terrestrial days every 48 days [29], in a long-term eclipse that points to a circumstellar disk of little objects as the cause, not a defined (planet) body. Equally, huge quantities of water vapor have been identified around CW Leonis [30], likely indicating that its recent increase in luminosity is vaporizing a large population of icy bodies orbiting around it. And the chemistry of the protoplanetary disk around Beta Pictoris suggests the existence of ice masses. So, the processes summarized here seem to be possible in worlds around other stars, highlighting the old question about chance and necessity in the origin and evolution of life.