Comets and Their Connection to the Origin of Life on Earth

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Abstract

Comets are fascinating astronomical objects, as they provide a deep insight into the Earth's history. A well-studied example is 67P/Churyumov-Gerasimenko (67P), the focus of Rosetta's soft landing mission in 2014, in which the amino acid glycine was unambiguously detected for the first time. Rosetta's findings are presented here in the broader context of cometary studies and the search for the origin of life on Earth. Identifying organic compounds and elements essential to life suggests that comets could have supplied the Earth with various prebiotic chemicals. Moreover, comets contain water, although studies of hydrogen isotopes showed comets were not a significant source of the Earth's oceans, compared to asteroidal planetesimals. Further research into comets is likely to reveal more about the formation of the Solar System, with a multitude of spacecraft missions currently being planned to investigate the beginnings of life on Earth.

Introduction

In our Solar System, there are around 17 Earth masses of comets, most originating in the Oort Cloud and Kuiper Belt regions [1]. The Oort cloud is located beyond Pluto's orbit, around 2,000–100,000 AU (1 AU = 150 million km) from the Sun, and contains mostly long-period comets (LPCs) [2]. The Kuiper Belt lies at around 30 - 50 AU from the Sun, and is thought to be the origin of Jupiter-family comets, whose orbits are in the vicinity of Jupiter's orbit. With periods of less than 20 years, they belong to the class of short-period comets (SPCs), alongside 1P-type comets [3].

Comets are composed of frozen rock, dust, and gas leftover from the formation of the Solar System, now locked into orbit by the Sun's gravity [4]. In the early Solar System, they contributed towards building the Sun and planets, which formed by continuously colliding together. The solid, rocky, frozen central part of a comet typically a few km in diameter is referred to as the nucleus, while volatile compounds form an atmosphere known as the coma [5]. When a comet moves into the Sun's proximity, some ice heats up and sublimates, causing a surrounding halo of gas and dust [6]. Part of this coma is blown away by solar radiation, forming a so-called comet tail, with separate ionic and dust features. The ion tail will always point away from the Sun because the Sun's radiation pressure far exceeds its force of gravity, which would attract the ions towards the Sun

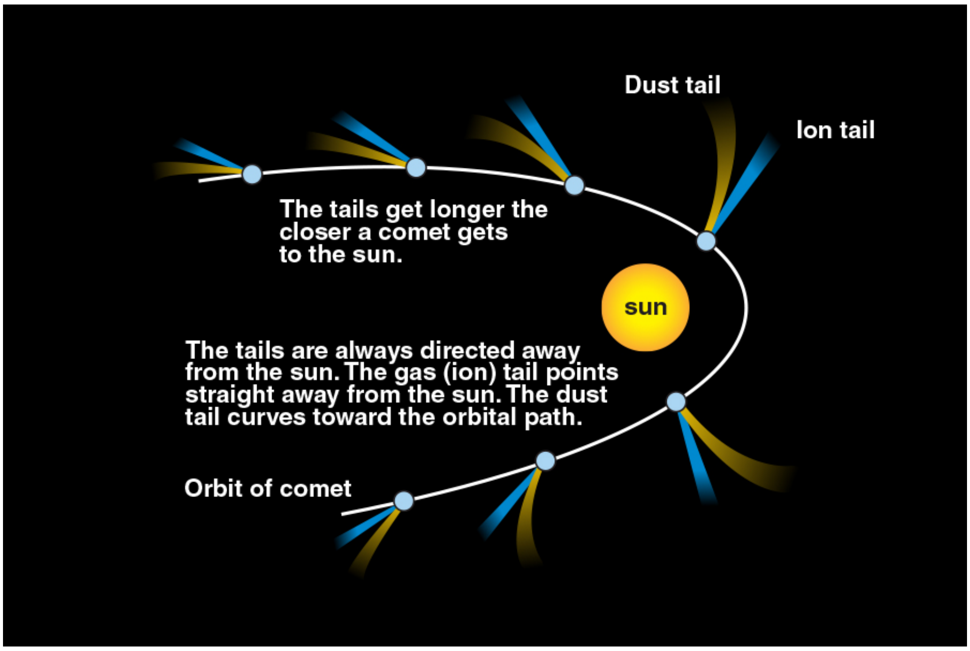

Figure 1: Shows the ion and dust components of a comet tail. When a comet gets closer to the Sun, the surface ice on the comet sublimates due to the increase in heat, causing the coma to be blown away into a larger tail [8].

[7]. The dust tail also points away from the Sun, but cures slightly due to the comet's velocity (see Figure 1).

Comets spend most of their time far away from the Sun because of their highly elongated elliptical orbits. Hence, they rarely interact with other Solar System bodies, making them valuable sources of data about the past. Studying their compositions is crucial to understanding the early Solar System, as they also contain many vital ingredients for life, such as water. Comets remain to be investigated in more detail, as only one mission to date has undertaken a "soft landing" on a comet for direct measurements. 80% of its planned first science sequence was completed, although complications rendered it not as successful as hoped [9].

Investigating Comets

A comet's size renders ground observations limited, although partial composition analysis can be made via spectroscopy and photometry of their comae. Spectral Analysis of 1P/Halley (1P) taken from 1986 surface observations revealed a cocktail of organic compounds along with water to be prominent in its coma [10]. The presence of both of these makes these results extremely relevant to life on Earth.

Compositional studies of comets have only been performed in the past 60 - 70 years, and in total only 8 comets were deeply investigated by spacecraft. Spacecraft based observations have been far more influential. The first spacecraft to fly by a comet was NASA's International Cometary Explorer (ICE) mission, which passed Comet 21P in 1985. In doing so, ICE confirmed the theoretical models of how the ion tails of comets are formed as they move through the inner Solar System [11]. In 1986, an "armada" of 5 spacecraft, listed in Table 1, visited 1P. The most notable of these, ESA's Giotto,

Table 1: Five internationally operated spacecraft visited 1P in 1986 - named the “Halley Armada”.

Spacecrat	**Operator**	**Notes**
Giotto	ESA	Ammonia and hydrocarbons were detected [12].
Vega 1/2	Soviet Union	Both spacecraft experienced camera malfunctions [13] experienced camera malfunctions
Suisei	ISAS	Made UV observations of 1P’s as well as Solar Wind interactions [14].
Sakigake	ISAS	First spacecraft of the armada to arrive, reference craft for rest of the armada [15].

revealed the presence of ammonia, methane and other more complex hydrocarbons in trace quantities within 1P’s nucleus [12].

Recent missions have included NASA’s Stardust spacecraft performing a fly-by of 81P/Wild in 2004, during which a sample of dust from the comet’s coma was collected and returned in an aerogel ‘net’ [16]. The returned material collected by Stardust had a combined mass of 1 mg, which notably contained glycine - extremely relevant to the discussion on the origin of life [17]. Another intriguing finding of Stardust was the presence of chondrite material on 81P/Wild, which is typically associated with asteroids and meteorites [18].. This demonstrated that compositionally, asteroids and comets are much more similar than thought, while also reinforcing the possibility that comets were a source of the Earth’s oceans.

Another notable NASA mission is Deep Impact, which involved a craft purposefully impacting into 9P/Tempel in 2005 [19]. In doing so, patchy water ice was found [20], marking the first-time water had been detected on the surface of a comet. By far the most insightful mission has been ESA’s Rosetta/Philae spacecraft, arriving at 67P/Churyumov-Gerasimenko (67P) in 2014. Rosetta was the first cometary orbiter, while Philae performed the first and only soft landing on a comet.

The summation of the knowledge obtained from the available techniques and technology is varied and often specific to certain comets. Using space and ground-based telescopes, their rotational period, direction of spin axis, and rough shape can be identified [21]. This is a crucial step before landing a craft on a comet can be tempted. The Philae lander included various onboard spectrometers in order to provide information on the composition of the comet’s surface, a radio wave detector to allow for radar scanning of the interior of 67P, and a multitude of internal sample testing equipment for samples taken using the craft’s drill. Its rough landing ultimately meant no samples could be taken, although the lander did ascertain 67P’s solid ice mixed with dust composition and the details of the composition of its water [22]. A high number of organic (carbon-rich) compounds were also detected on its surface. Crucially, Rosetta detected phosphorus compounds on 67P [23], meaning all of the elements essential for Earth life have been found on comets.

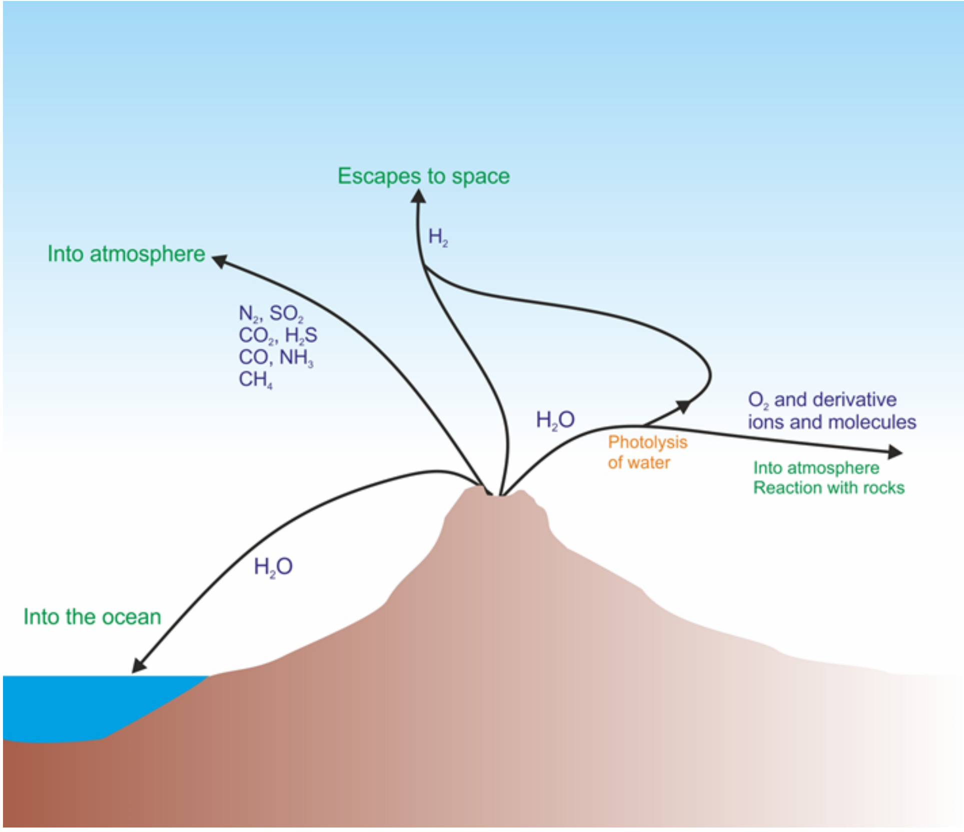

Figure 2: Gases produced by volcanic outgassing that greatly contributed to making Earth's atmosphere more habitable. The gases are present because of the impacts of comets and planetesimals during Earth's formation [24].

History of the Early Earth

When the Earth formed in the early Solar System, three major energy transfers occurred. One was caused by radioactive elements [24], and the other by collisions from planetesimals in the early protoplanetary disc, which added to gravitational forces compressing material when it gathered in the newly forming Earth. These energy sources kept the planet in a molten rock state, but it cooled as the compression and collision energies dissipated. Eventually, the Earth's internal temperature reached the melting point of iron, and it underwent so-called global chemical differentiation. In the course of this process, heavier elements such as iron sank to the core, while lighter elements like silicon floated upwards. This process was completed approximately 4.3 Ga ago (Ga equals 1 billion years), resulting in the composition and structure we are familiar with today [25]. The early Earth's atmosphere is thought to have been composed primarily of helium and hydrogen gas that could not be contained by the Earth's gravity, and consequently escaped into space [26]. For the next several hundred million years, volcanic out-gassing created a thicker atmosphere composed of a wide variety of gases that came from the mass accreted when the Earth was forming. Figure 2 shows various gases that escaped into the atmosphere, meaning the contributions of comets and planetesimals during the Earth's formation ultimately lead to today's habitable atmosphere.

During the early Solar System (4.1–3.9 Ga ago), there is evidence of heavy bombardment from extraterrestrial material in the form of giant craters on the inner planets (Mercury to Mars) [27]. It is theorised that during this period, the Earth accreted prebiotic organic molecules crucial for the origin of life from the impacts of carbonaceous asteroids [28]. These impacts would have had a strong effect on the environment. Any organics would not have survived at the site of impact, and rock and water would be vaporised. If the impact of planetesimals were in the oceans, it would generate giant tsunamis around coastal areas. This would pose a threat to the progression of life, as the larger impacts have been suggested to have vaporised the top few hundred metres of the ocean due to the extreme atmospheric temperature generated (above 2000K) [24].

The early and modern-day Earth have several similarities. Early oceans and continents would provide habitats for life, and through the possible process of ocean evaporation and consequential precipitation, there could have been freshwater bodies on land that provided homes for certain microorganisms [24]. The key difference between modern and early Earth is that the latter's atmosphere lacked oxygen and therefore any ozone protection [29]. Without this protection, UV light from the Sun with wavelengths of 200nm could have reached the surface of the Earth, causing biological damage to life. Fortunately, particles of soil, iron, rock and other substrates rapidly and significantly diminished UV radiation, protecting the biological matter. However, the UV dose was still significant in preventing anything to colonise the exposed surface of the early Earth [29].

Cometary Impacts and Water on Earth

Due to the bombardment of the early Earth with comets, it has been theorised that cometary impacts could have been a source of the water forming the Earth's oceans [24]. This would have great relevance to the emergence of life on Earth, as oceans contain numerous environments where life could have originated, such as hydrothermal vents.

Several scenarios predict minimal to major contributions of comets to oceans, and a useful way to distinguish between them is by comparing the so-called D/H ratio of terrestrial water and that in comets [30]. D/H is the ratio between deuterium (D, a form of hydrogen with an additional neutron) and hydrogen (H, with only one proton and one electron) found in the water molecule, with a value of 1.55×10^{-4} for the Earth's oceans [24].

Multiple astronomical, as well as in-situ measurements, revealed LPCs to have a D/H ratio of about twice the Earth's, while the Rosetta Orbiter Spectrometer for Ion and Neutral Analysis (ROSINA) found the D/H ratio of comet 67P to be three times the terrestrial value, as shown in Figure 3 [30]. This suggests comets were not a major source of water in the Earth's oceans.

Instead, studies of chondrites – meteorites rich in water, originating in the asteroid belt – show a D/H ratio similar to the Earth's. Such asteroids and comets are thought to have contributed around 10% or less to oceans. Thus, one major hypothesis suggests that the early Earth gained most of the water by accreting asteroidal planetesimals. Incorporated into the planet, this water would later be degassed and condensed on the surface into oceans [24].

Although comets most likely did not contribute majorly to oceans, cometary impacts are still of relevance to the origin of life. The heat generated during a collision can produce a hydrothermal system within the crater, in which the water and organic compounds deliv-

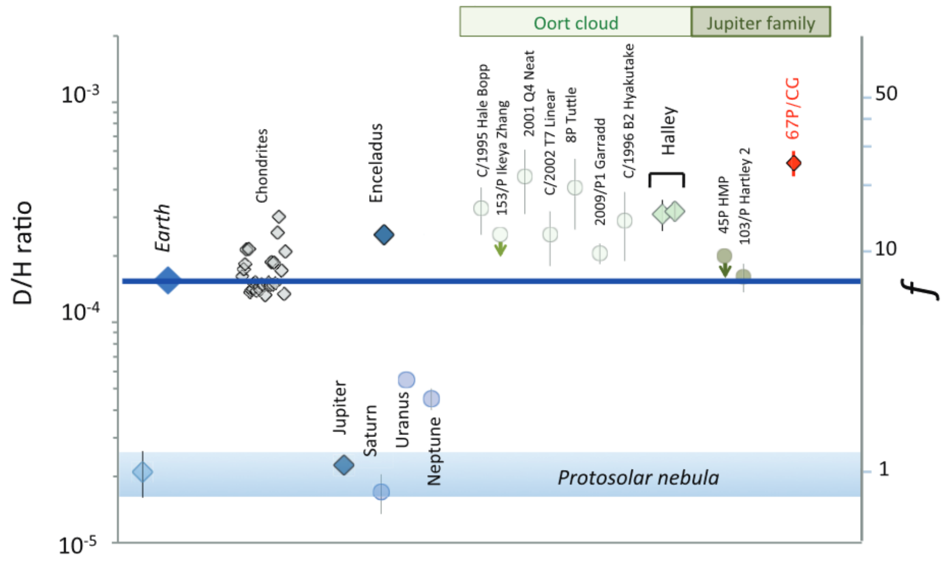

Figure 3: D/H ratios in water on several Solar System bodies, including Jupiter-family (SPCs) and Oort cloud comets (LPCs). The blue horizontal line shows the terrestrial D/H ratio. Cometary ratios are clearly higher, while those of chondrites are comparable with the Earth's value. Note, the objects are arranged along an arbitrary horizontal axis, according to their type (planets, asteroids, comets) [30].

ered by the comet are deposited. Thus, impact craters could be a suitable environment for the chemical reactions producing life [24].

Organic Compounds Found in Comets

Organic molecules, including the precursors to life, can form in the interstellar medium [24]. Comets preserve material from the Protosolar Nebula, from which the Solar System formed [30] [31]. As they travel inwards from the outskirts of the Solar System, they can deliver some of this material to planets via collisions. It is estimated that 4 Ga ago, comets delivered around 10^5 to 10^6 kg of organic material to the Earth [24]. Missions like NASA's Giotto and ESA's Rosetta have detected organic compounds in cometary comae, including those that could have possibly played a role in the origin of life on Earth. Elements relevant to biology include carbon, oxygen, nitrogen, hydrogen, and phosphorus [32].

Comae are usually depleted in volatile nitrogen. For comet 67P, ROSINA identified this depletion due to the nitrogen being tied up in ammonium salts [31]. This is relevant to astrobiology, as ammonium salts are precursors to amino acids like glycine, which are in turn building blocks of proteins and enzymes [33]. ROSINA also detected glycine itself in the coma of 67P by ionising the volatiles as the comet approached the Sun. Terrestrial contamination was ruled out by observations, making this the first unambiguous detection of glycine on a comet [23]. Since amino acids are essential to life on Earth, this suggests comets could have contributed to the origin of life.

Studies of meteorites (debris from objects like asteroids and comets [34]) have found numerous amino acids, identifying around 70 in chondrites, including those found in terrestrial biology. Notably, life on Earth contains so-called "L" forms of all common

Figure 4: Chirality in amino acids - due to asymmetry, two mirror forms called "D" and "L" exist, as shown. Source [35].

amino acids. Since these are asymmetric molecules, two different mirror images labelled "L" and "D" can exist, depending on the atom positions (Figure 4) - this phenomenon is known as chirality. Enrichment in "L" forms of amino acids was also found in meteorites, suggesting that chirality could have had an extraterrestrial origin [24].

Besides amino acids, Rosetta detected phosphorus on 67P, which is an essential ingredient of cell membranes and DNA [32]. Overall, the mission successfully demonstrated that comets could have been a vital source of prebiotic chemistry on Earth. The importance of in-situ observations of comets is highlighted by the NASA Astrobiology Roadmap, listing cometary samples as a key contribution to the search for prebiotic compounds and signs of life in extraterrestrial environments [36].

Future Missions

The future of cometary exploration and observation is bright and highly varied. The jewel in the crown of future explorations for the next 20 years will undoubtedly be the ESA/JAXA Comet Interceptor (herein, COM-I) mission scheduled to launch in 2028. The mission aims to send a spacecraft to a (currently unknown) LPC, and it will be the first spacecraft to do so. Upon arrival, the spacecraft will split into three, building up a "live" 3D picture of the comet throughout the flyby. LPCs are predicted to be compositionally and structurally "pristine", meaning they have undergone little to no modification when passing through the inner Solar System, unlike SPCs [37]. By studying LPCs, it is hoped to compare observations of properties such as chemical and physical composition, outgassing and rotation to those observed previously of SPCs. For example, using the MANIaC Mass Spectrometer, that is partially based on the similar ROSINA-RTOF spectrometer used by Rosetta, it will be possible to take measurements of the D/H Ratios of the water and various other organic compounds detected in comets previously [38]. This will add to the evidence on the origin of the source of the Earth's water [30].

There are, however, limitations to what COM-I can achieve due to the short mission duration, combined with the relative speeds and inclinations of any candidate comets being very high. It will be impossible for the spacecraft to enter orbit around the comet, meaning only a flyby will be possible [37]. Thus, it will only closely observe the target over a short time period. A mission similar to Rosetta capable of entering orbit with (and possibly landing on) an LPC is yet to be proposed or planned. This challenge could be at least partially tackled with coincident ground-based observation, similar to those necessary for the success of Rosetta and Philae.

At present, the European Southern Observatory's Extremely Large Telescope (ELT) is expected to be operational by 2027, fitting within the mission schedule of COM-I. The ELT's wide bank of instruments, in particular the Mid-IR ELT Imager and Spectrograph (METIS), will be able to provide multiple measurements of D/H ratios over a long time at resolutions not previously achievable by ground-based observations [39]. Such measurements could complement the data collected by COM-I. Going further, there are numerous ideas in the pipeline waiting to be developed; one in particular being to position a spacecraft in a heliocentric orbit with the intention to make close, regular observations, focusing on Sun-Grazing/Skirting Comets at their perihelion (closest point to the Sun in an orbit). Such observations could be very useful in measuring the composition of cometary interiors as they disintegrate [40]. As for imminent data, one mission, NASA's New Horizons, may be able to swing by a comet within the Kuiper Belt in the near future, if one can be found that is close enough to the spacecraft's current trajectory. Presently, a suitable target is yet to be found. Overall, while ground-based telescopes are improving sufficiently in taking detailed measurements of cometary composition, spacecraft still by far provide the best tool for taking these measurements.

Conclusion

The observations made to date have shed light on many potential theories for the origin of Earth's life. There have been several precursors to life found on comets, including phosphorus and glycine, which are found in DNA and proteins, respectively. However, the water detected on comets thus far does not share the same D/H ratio as the Earth's oceans, implying different bodies such as asteroids and planetesimals were the major sources of terrestrial water. Further studies will need to be conducted in future missions to make more definitive conclusions. There are currently several active and planned missions that aim to specifically investigate long-period comets.

Instead of ground-based observations, spacecraft will take measurements at much closer proximities to the comets themselves, potentially detecting compounds that could not be found otherwise. In spite of the long waiting periods due to planning and travelling of spacecraft, the potential for future missions is promising. Once we know more about the origin of life, the search for habitable environments outside our Solar System may become more trivial, potentially answering questions about the existence of life elsewhere in the Universe.

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