Comets: Where We Are, How We Got Here, and Where We Want To Go Next

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We introduce the principal mysteries surrounding comets; discuss the proposed importance of comets to the origin of water and organic compounds in the inner solar system; and summarize the history of cometary observation, study, and exploration over the past 22 centuries.

Keywords: comets, water, organic compounds, Oort Cloud, Kuiper Belt, solar system

INTRODUCTION

Comets are the largest objects in the solar system. While the nuclei of comets are generally less than 50 km across, the coma (atmosphere) may be larger than the Sun, dust tails can be up to 10×10^6 km long, and gas ion tails have been observed to extend as far as 550×10^6 km (Yeomans 2005) (Fig. 1). The largest observed gas ion tail would, thus, almost extend from the Sun to Jupiter. For most scientists, it is the periodic presence of an atmosphere and gas and ion tails that distinguish comets from asteroids (Gene Shoemaker, private communication, 1995), although there is actually a complete continuum between comets and asteroids. To learn more about asteroids, the so-called "vermin of the heavens", see the "Asteroids" issue of *Elements* (February 2014).

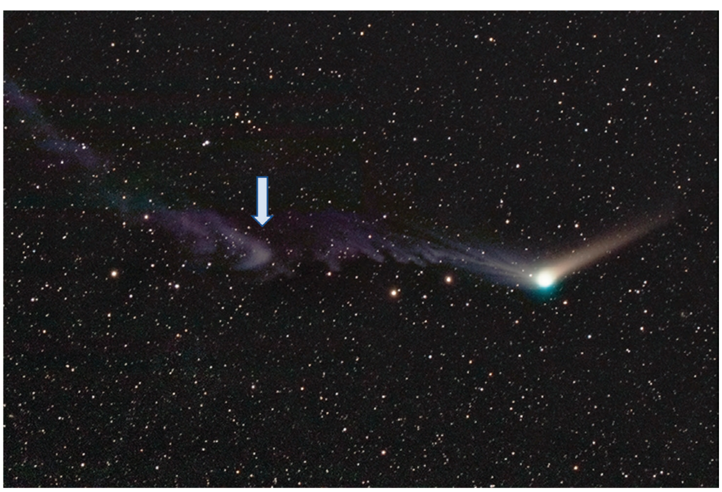

Figure 1 Twisted gas ion tail of comet Catalina (C/2013 US10) in December 2015 extends to the left of the nucleus and coma (directly away from the Sun) while the dust tail extends to the right, along the comet's orbital trail. The brighter region of the ion tail (arrowed) is a portion of the tail that was detached by a solar coronal mass ejection (a huge explosion of plasma, with embedded magnetic field, from the Sun's corona). Image from Cometwatch UK.

There are many basic questions to be answered about comets. What role did comets play in the origin of life on Earth and the delivery of water to the inner solar system? Observations of cometary comae reveal that they release large quantities of volatiles. But is this water isotopically identical to that of Earth's water? Did cometary solids in the nuclei ever experience reactions with liquid water, or was that water always present in a frozen state? Beyond that, what is the structure of water ice in comet nuclei, does it preserve crystal structures revealing formation at the very low temperatures of interstellar space? How complex was organic evolution in cometary nuclei, and how well do the organics currently detected in nuclei satisfy presumed requirements for life's origins? Where did the constituents of comets form, and where did the final assembly of their nuclei occur? Did these processes occur only in the outer edge of the solar nebula, or did some solids form near the early Sun? How well is pre-solar material preserved in cometary nuclei, and are some nuclei actually visitors from other solar systems? These are among the basic questions that have long intrigued scientists, and it is only recently that some answers have been found.

Comets have been the focus of intense human excitement, curiosity, and downright fear for as far back as we have records, as witnessed by paleo-astronomical carvings, the earliest written records, the Bayeux Tapestry, and many disaster films. Figure 2A shows the first clearly recorded renderings of comets, on a silk manuscript from 2nd century BC China. Many cultures considered comets omens of ill fortune, possibly because they appeared to cut across the sky, the presumed solid celestial spheres, and displayed other ominous behavior. It is interesting that comets have been considered bad luck by practically all human cultures, despite it being only during the past century that we have had any real understanding of what they are and their threat to civilization.

HISTORY OF COMET RESEARCH

It is appropriate to give a brief summary of the history of comet observations, to set the stage for this issue's articles.

Orbital Motion and the Oort Cloud

The unprecedented planetary observation campaign by Danish nobleman and astronomer Tycho Brahe (1546–1601) provided the first clear demonstration that the horizontal parallax of comet C/1577 VI (determined in

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THE NAMING OF COMETS

Comets have always been named in a logical manner, but unfortunately the logic has changed through the years. The earliest schemes named comets after the year in which they were observed: for example, the *Great Comet of 1882*, discussed in this article. Another convention arose using the names of people associated with the discovery or the first detailed study of each comet: for example, *Halley's Comet*. Dedicated comet explorers often had multiple discoveries to their credit, for example *Comet Wild 2* and *Comet Shoemaker–Levy 9*. In the past century significant improvements in observing technology and dedicated searches (some automated) have resulted in a massive increase in the number of comet discoveries, resulting in the creation of numeric naming schemes. In the current system, the name is based on the type of orbit ("P" for periodic, for example, and before 1990 there was often a number suffix applied to this letter – such as 81P for comet Wild 2) and the date of discovery followed by a letter indicating the half month of discovery. For example; comet P/2010 B2 is the second (2) periodic (P) comet discovered in the second half of January (B) of 2010. This system is sometimes stretched to the limit – Comet C/2017 U1 ("C" for non-periodic, "2017 U1" for first comet discovered in the first half of November 2017) was later reclassified as asteroid A/2017 U1 ("A" for asteroid misidentified as a comet), and ultimately reclassified as the first unambiguous interstellar visitor to our solar system 1I/2017 U1 ("1I" for first identified interstellar object), and given the unique name 'Oumuamua. 'Oumuamua is now reckoned to be a sliver of a comet (or related body) that was ejected from its home solar system, becoming an interstellar voyager.

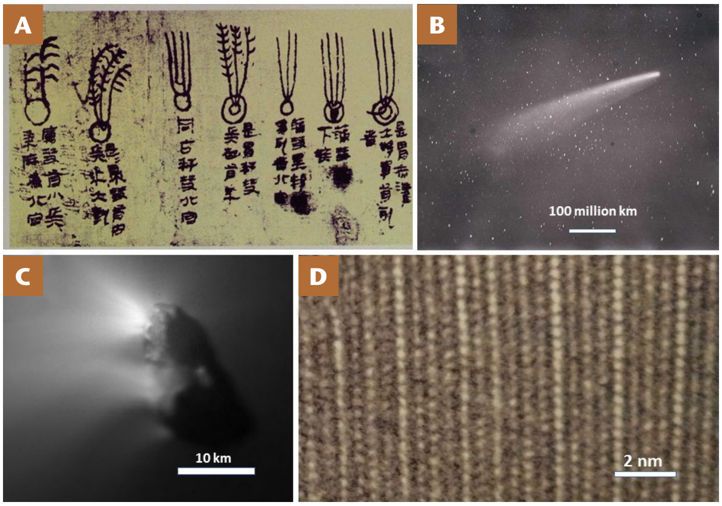

FIGURE 2 Comet images across 22 centuries. (**A**) Comets detailed on a Chinese manuscript, ink on silk, 2nd century BC, Han dynasty, unearthed from the Mawangdui tomb. Various comet tails are recorded, and these are the earliest known unambiguous images of comets. (**B**) David Gill's photograph of the Great Comet of 1882 (C/1882 R1). IMAGE FROM SOUTH AFRICAN ASTRONOMICAL OBSERVATORY ARCHIVES. (**C**) *Giotto* spacecraft image of the nucleus of comet 1P/Halley, collected 13-14 March 1986. IMAGE BY THE HALLEY MULTICOLOR CAMERA TEAM, GIOTTO PROJECT, ESA. (**D**) High-resolution transmission electron microscope image of the structure of olivine, from an 81P/Wild 2 coma grain returned to Earth by the *Stardust* spacecraft in 2006. IMAGE FROM NASA JSC.

1578) was less than 15 arcminutes, indicating a distance further away than the Earth's moon, and proving that comets were not atmospheric phenomena as had apparently been believed for thousands of years. In 1687, Isaac Newton applied his new theory of gravitation to the orbits of comets, showing that they moved in highly elliptical orbits, and his colleague Edmond Halley (1656–1742) proposed the periodic nature of comet 1P/1682 Q1. The subsequent sighting of this object, now renamed "Halley's" comet by Johann Georg Palitzsch in 1758, proved that the law of gravitation was valid out to the outer solar system (at least). Thus, comets were at the heart of a major step in understanding the mechanics of the universe.

During the early 19th century, Friedrich Bessel and Wilhelm Olbers ascribed some comet tail phenomena to a repulsive force acting away from the Sun, early evidence for the solar wind (Festou et al. 2004). A convincing link between meteor showers and comets was first forged by Giovanni Schiaparelli in a series of papers in the 1860s to 1870s (e.g. Schiparelli and Denza 1872). Schiaparelli observed that the Perseid and Leonid meteor showers were clearly linked with the passage of Earth through the orbital paths of comets 109P/Swift–Tuttle and 55P/Temple–Tuttle, respectively, and the gradual loss of dust from these bodies. In this issue of *Elements*, Jenniskens and Popova (2018 this issue) have much more to say about the implications of this observation. There is also much more about the resultant interplanetary dust and its study in the recent "Cosmic Dust" issue of *Elements* (June 2016).

The first comet to be imaged by photography was C/1858 L1 Donati, in 1858. Unfortunately, the image of the entire comet, taken by the English artist William Usherwood, has not survived, and a later one of just the comet's head, made by George Bond, is not very clear. The earliest surviving image of an entire comet appears to be that of the Great Comet of 1882 (Pasachoff et al. 1996) (FIG. 2B). About this same time period, the first spectroscopic observations of comet comae were made (1864).

In 1950–1951, three new ideas were advanced which revolutionized our understanding of the nature of comets. Building on the work of others, Fred Whipple formulated his "icy conglomerate" model for comet nuclei (Whipple 1950, 1951). Jan Oort inferred, from his dynamical studies of the observed distribution of cometary orbits, the existence of a realm of icy bodies beyond the planets at some 50,000 and 200,000 astronomical units, or AUs, from the Sun (an AU being the average Earth–Sun distance) (Oort 1950). This population of comets at the edge of the solar system is now called the Oort Cloud (FIG. 3). Oort estimated that the total mass of material in this cloud to be in excess of 10^{25} kg, or >5 Earth masses. The Oort Cloud is currently envisioned as having a spherical outer shell and a torus-shaped inner cloud (the latter first proposed by Hills 1981), which replenishes the outer shell. There have, as yet, been no direct images of our Oort Cloud, but similar clouds have been observed around other stars. FIGURE 4 shows a radio image of a presumed cometary ring around the star HD 181327 (Marino et al. 2016). Finally, in 1951, Ludwig Biermann provided a correct explanation that the solar wind causes motions of cometary plasma tails (Festou et al. 2004). Thus, in a little more than one year the true nature and origin of comets came into much better (but not yet complete!) focus. Whipple's work, in particular, immediately explained several previously mysterious properties of comets, namely their large gas and dust production rates, the presence of jets of gas and dust, the manner by which this mass outflow affects cometary orbital motion and spin behavior, and the reason that most comets survive close encounters with the Sun (Festou et al. 2004). We note that

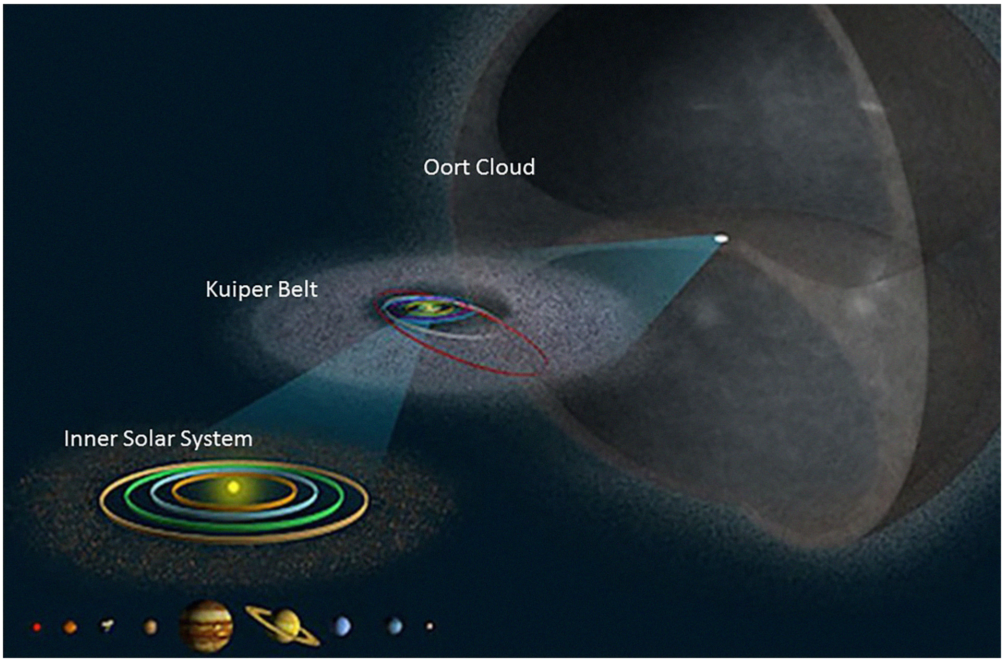

Figure 3 Cartoon showing the relative positions and scale of the inner solar system, the Kuiper Belt, and the Oort Cloud. From Jedimaster Wikipedia Commons.

Fred Whipple designed a new type of bumper shield to protect allied tanks during World War 2, and, 50 years later, NASA's *Stardust* spacecraft used a similar "Whipple shield" for protection from high-velocity coma dust impacts from comet 81P/Wild 2. At the age of 92, Fred was an honored guest at the 1999 launch of the first spacecraft to return comet samples to Earth. The article by Brownlee et al. (2018 this issue) describes the recent history of comet exploration spacecraft missions.

The recent discovery and characterization of a tremendous population of bodies in orbits beyond Neptune has verified the predictions by Kenneth Edgeworth (in 1943) and Gerald Kuiper (in 1951) of the existence of such objects as the source of most short-period comets (Jewitt and Luu 1993). Pluto was the first of these bodies to be discovered, but as searches demonstrated their immense number, Pluto was demoted from "planet" down to "dwarf planet" status. Now Pluto is considered merely one of the largest known bodies in the "Kuiper Belt", as this portion of our solar system is now known.

The study of comets has now expanded from being the territory of Earth-bound astronomers to the targets of increasingly complex uncrewed spacecraft. In 40 years, twelve spacecraft have successfully visited eight comets, representing the determined efforts of engineers and scientists from 25 nations, 22 of which are part of the European Space Agency. These missions are described by Brownlee et al. (2018 this issue). We will describe here only a novel feature of one of these missions – the very first one. The *International Sun–Earth Explorer 3*, or *ISEE-3*, was launched in August 1978 to study space weather. At the completion of its primary and during its secondary missions, *ISEE-3* was "appropriated" to become a cometary explorer. In 1982, Robert Farquhar (the grand wizard of celestial mechanics) and David Dunham designed and implemented a dazzling series of lunar orbits and engine firings that sent the spacecraft away on a stable orbit between the Earth and Sun, to perform the first spacecraft encounter with a comet (Farquhar 2011). This action reportedly took some of the *ISEE-3* scientists, who were still using it to collect data, by irritated surprise. Renamed the *International Cometary Explorer* (*ICE*), the spacecraft passed though the tail of comet 21P/Giacobini–Zinner on 11 September 1985, and, in the following year, joined the international fleet of spacecraft that welcomed comet 1P/Halley back to the inner solar system. The *ICE* spacecraft made observations of comet tail plasma and ion characteristics.

Comet Composition

A focus of spacecraft and ground exploration of comets by several generations of scientists has been the nature of their volatile inventories (A'Hearn 1983; A'Hearn et al. 1995), as described by Yabuta and coauthors (2018 this issue). Comets have long been touted to represent the most unaltered of early solar system materials, and, indeed, some scientists suggested that they might consist principally of pre-solar or interstellar materials (Russell 2018 this issue). It was commonly believed that the cometary solids would consist of materials formed at the outer rim of the solar system, well beyond the distance where water ice was a stable phase (the "snow-line"), and would, thus, contain an abundance of volatiles, with nonvolatiles principally consisting of unaltered to annealed nebular condensates. As reported by Brownlee et al. (2018 this issue), all these proposals proved to be incorrect for comet 81P/Wild 2. The question now is how representative 81P/Wild 2 is of Jupiter-family comets (a group of short-period comets whose orbits are controlled

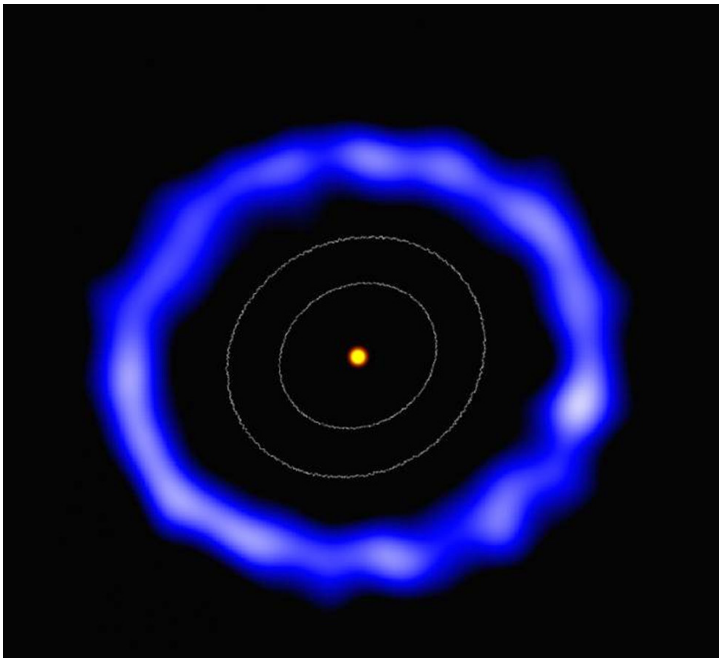

Figure 4 Atacama Large Millimeter/submillimeter Array (ALMA) image of the ring of dust and carbon monoxide emission around the star HD 181327 (false color image), proposed to be arising from a shell of comets. The white contours represent the inner and outer dimensions of the Kuiper Belt in our solar system. Photo from Amanda Smith, University of Cambridge (UK).

by Jupiter's gravity). That can only be answered by Earth-based laboratory analyses of samples returned from other comet nuclei and comas.

Or perhaps not! Matthieu Gounelle (of the Muséum National d'Histoire Naturelle, Paris, France) has argued that some very volatile-rich meteorites derive from comets, most notably the Orgueil CI carbonaceous chondrite, which fell in a very well-witnessed shower of stones in southwestern France on 14 May 1864 (Gounelle 2011). The CI chondrites are one of the most water- and organic-rich types of meteorites and have experienced pervasive alteration by liquid water. Gounelle used the descriptions of the Orgueil fall to reconstruct the orbit of the meteoroid ("meteoroid" being the meteorite while still in space). Orgueil's orbit (as well as the atmospheric trajectory) was fairly well-constrained by the 150-year-old observations and was consistent with that of some comets. Until recently, the water D/H ratio measured from a handful of comet comae (all coming from the Oort Cloud) was always roughly twice that of carbonaceous chondrites in general and of Orgueil in particular. This discrepancy was used to question the cometary origin of the Orgueil meteorite. This changed with the discovery that the coma of Jupiter-family comet 103P/Hartley 2 had a water D/H ratio identical (within uncertainties) to that of the Orgueil meteorite (Hartogh et al. 2011). This observation supported a link between CI chondrites and at least some comets. If verified (still a big *if*), a cometary origin for Orgueil implies that some comets are heavily chemically processed, an attribute not observed with the 81P/Wild 2 samples. An intriguing point is that Orgueil is no ordinary meteorite. Its bulk composition is the closest of any meteorite to that of the solar photosphere (the Sun's visible surface).

THE FUTURE OF COMET RESEARCH

Over the past 22 centuries the resolution of comet images has increased from distant views of entire comets and their coma to atomic-scale images of individual mineral grains returned to Earth from comet 81P/Wild 2 by NASA's *Stardust* spacecraft (Fig. 2D) – an amazing 17 orders of magnitude (see Fig. 2). In the latest giant step, the *Rosetta* spacecraft orbited, and deposited a probe on comet 67P/Churyumov–Gerasimenko, as described by Grady et al. (2018 this issue). In many ways, we live at the perfect time to be "cometologists". However, the mission that most cometologists most desire to see would be a truly cryogenic (<–180 °C) comet nucleus sample-return mission. Only such a mission will permit comprehensive understanding of outer solar system water, organics, and volatiles, and their role in the genesis of life in the inner solar system. Such an endeavor is still just a dream and is unlikely to occur in our lifetime. There is still a chance for a comet nucleus sample-return mission to be approved in the coming decade, possibly with a subzero returned sample. However, a fully cryogenic sample-return mission would require considerable new engineering and carry a multibillion-dollar price tag. There would also be enormous challenges for sample handling, curation, and analysis of cryogenic samples back on Earth. Nevertheless, planning for such a mission has been gradually unfolding for decades … and we are nothing if not hopeful.

ACKNOWLEDGMENTS

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