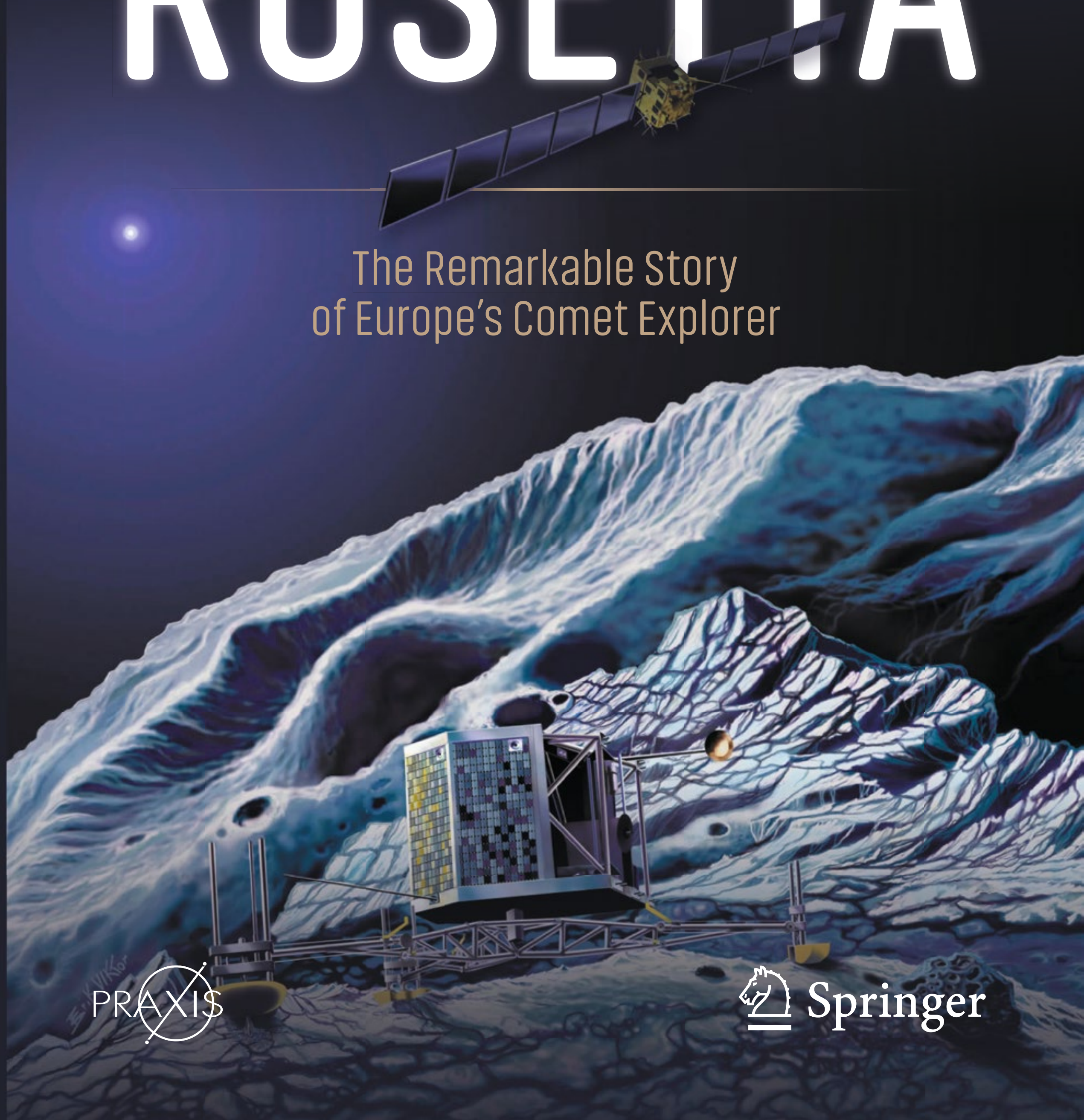
PETER BOND

ROSETTA

The Remarkable Story of Europe's Comet Explorer



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This book is dedicated to the thousands of people who committed many years of their careers to the Rosetta mission. Through their efforts, the dream of a European comet chaser became a reality, revolutionizing our knowledge of these once-mysterious cosmic icebergs.

Foreword

Writing just before the Space Age dawned, Roland Barthes described the Citroen DS car as the modern equivalent of a medieval cathedral, conceived by passionate, unknown artists but seen with awe by everybody. I have always felt that the grand missions of space exploration are similar. Like the great cathedrals, they are built by teams of highly skilled people working together, but most of the names of those involved are completely unknown. There is no doubt in my mind that the passion and commitment in the science and engineering teams for these missions must surely reflect that which drove the medieval craftsmen in their skilled tasks.

Peter Bond reports here on the full history of the Rosetta space mission, one of the great steps to explore not only the Solar System as it is today, but also to reveal critical clues to help to decode how it formed. No doubt there were ecclesiastical dreamers behind the conception of a cathedral, and there must have been both sacred and secular authorities whose endorsement and finance had to be secured before it could be built.

It is just so in the grand schemes of space exploration. The Rosetta project involved much politics and lobbying to get the resources required to ensure that everything could come into place. Ultimately, as Barthes said about the cathedrals, it was the craftsmen whose skills and artistry finally delivered the dream, and it fell to the engineering and science teams working together to create the final achievement. Peter's book illustrates how an idea can grow, gather support, surmount obstacles, and eventually achieve a magnificent reality.

Rosetta was a European idea, and one where Europeans had to recognize that they had to be prepared to fall back upon their own resources. Although cooperation with the United States might bring the resources for even grander science, if the US was not ready to join in, Europe needed to go it alone. The European scientists and engineers would have to define what they could achieve with their own resources and, if necessary, accept, on their own, a host of new technical challenges.

It was not simple, and there was much argument and compromise on the way. Big problems needed addressing and resolving on the technical front. Rosetta produced technical advances such as developing solar panels that could operate five times farther from the Sun than Earth, and setting up a European deep space communications network that could monitor a craft far out in the Solar System – continuously, if necessary. Nonetheless, perhaps the most unnerving aspect was putting the spacecraft into hibernation and out of communication for just over two and a half years while it made its way out to rendezvous with its comet.

If the Rosetta project had its share of known challenges to deal with, it also had to face the unexpected. Perhaps the most dramatic event was the decision to delay the launch by a year due to a failure of the Ariane launcher in the month before the planned date in 2003. Having to store the spacecraft presented its challenges, but so did dealing with the cost of the delay, coupled with the fact that comets do not wait for late arrivals. Finding an alternative target became an urgent major task.

The new comet chosen, Churyumov-Gerasimenko, or 67P, turned out to be a very unexpected sight once Rosetta was close enough for imaging. Its resemblance to a 'cosmic duck' grabbed everyone's imagination, but also led to concern within the team as to how stable its internal structure was. However, rendezvous and insertion into orbit were accomplished, Philae was sent down to the surface, and, after a voyage around the Sun, the Rosetta spacecraft itself was deliberately dropped onto the surface at the mission's finale. At that point, I do not know how many people globally felt that a little part of them had been involved in the great adventure. What is clear is that everyone knew it was a great human achievement.

At various times, in the past 30 years, I had my own small part in the great adventure that was Rosetta. I relived many personal memories as I read this book. The Rosetta mission, as a true milestone in European space exploration, has found a very fine chronicler in Peter Bond.

David Southwood

After an academic career as a space scientist, including being Head of Imperial College London's Physics Department (1994-1997), David Southwood joined the European Space Agency in 1997. In 2001, he became ESA Science Director, retiring in 2011. He was president of the Royal Astronomical Society 2012-2014. He is currently a senior research investigator at Imperial College. He is a Fellow of the Royal Aeronautical Society, was awarded the NASA Distinguished Public Service Medal, and won the 2011 Sir Arthur C. Clarke award for space achievement. He is the past chairman of the Steering Board of the UK Space Agency and served on the Board 2011-2019. He received a CBE in the 2019 Queen's Birthday Honours for services to space science and industry in the United Kingdom and Europe.

Acknowledgments

I would like to express my sincere thanks and appreciation to everyone who kindly agreed to assist me in writing what I hope will become the definitive account of the remarkable Rosetta mission.

Most of the information about the early years of the mission's genesis and evolution came from documents and online status reports by the European Space Agency (ESA), NASA, and Daimler Chrysler Aerospace. The details of the mission itself were covered in great depth on the ESA science website and the website of the German Aerospace Agency (DLR), as well as the daily blogs written by Emily Baldwin, Claudia Mignone and Daniel Scuka.

The plethora of scientific results was summarized on the ESA science and exploration web pages and on the blog pages of the Planetary Society, edited by Emily Lakdawalla. Numerous papers detailing analysis of Rosetta's treasure trove of data were also made available in open source issues of leading scientific journals – Science, Nature, Monthly Notices of the Royal Astronomical Society, and Astronomy & Astrophysics.

The vast majority of the illustrations used in the book were provided by ESA, many of them originating with the German OSIRIS camera team. Holger Sierks, the OSIRIS principal investigator, kindly gave me his perspective on the debate regarding the public release of the high resolution images from this wonderful instrument.

I was pleased to be able to correspond with two people with whom I had worked at ESA, and who had played leading roles in the early years of the mission: John Ellwood, who was the project manager prior to Rosetta's launch, and Gerhard Schwehm, who was a leading light in the Giotto mission to Comet Halley and later became Rosetta project scientist. Both of them kindly read through early drafts of chapters and gave me their recollections of key moments in the mission's development.

The current project scientist, Matt Taylor, was also most helpful by reading the chapter about the science results and providing advice on other aspects of the book. Charlotte Götz, one of his colleagues, went out of her way to provide an updated plot of Rosetta's orbital distances after its arrival at Comet 67P/

Churyumov-Gerasimenko. Patrick Martin, the current Rosetta mission manager, kindly provided some historical information.

Sylvain Lodiot, who was deeply involved in Rosetta flight operations for most of the mission, not only read through several draft chapters but willingly gave his time to answer numerous requests for information and clarification.

Stephan Ulamec, the DLR project manager for the Philae lander, was an invaluable help by reading through the sections about the small craft which made history by landing on a comet.

David Southwood, the ESA Director of Science around the time that the Rosetta mission was launched, graciously wrote a Foreword which puts the wonderful achievements of Rosetta in perspective.

I also gratefully acknowledge assistance with the biographical section from Luigi Colangeli, Wlodek Kofman, Thurid Mannel, Stephan Ulamec, John Ellwood and Gerhard Schwehm. Those for Klim Churyumov and Svetlana Gerasimenko are largely based upon interviews that I conducted with them in 2014.

I am grateful to David M. Harland, who not only meticulously edited the manuscript but also improved the quality of several images, as well as to Clive Horwood of Praxis Publishing and Hannah Kaufman at Springer in New York, for their support throughout the development and completion of this endeavor.

Finally, I must thank my wife, Edna, for her support, forbearance and countless cups of coffee.

Preface

By the early 1980s, planetary exploration was dominated by the space superpowers, namely the United States and the Soviet Union. Eager to find a niche research area in which it could make a ground-breaking contribution, the European Space Agency (ESA) decided to focus on the smaller members of the Solar System, the comets and asteroids which represent ‘building blocks’ left over from the era of planet formation, some 4.5 billion years ago.

ESA’s first sortie into in-situ comet research was as a member of an international effort to study Comet Halley, which was returning to the inner Solar System in 1986 after 76 years in the frigid depths of space. Inspired by this once-in-a-lifetime event, ESA, the Soviet Union, and Japan sent an armada of spacecraft (the ESA one being named Giotto) to study the famous intruder at close range. The resulting treasure trove of data transformed the field of cometary research, and provided new insights into the early stages of how the planets came into being.

Even before the accomplishment of this pioneering endeavor was confirmed, ESA and NASA scientists were coming together to discuss the next giant leap in the exploration of comets and asteroids. Their ambitious vision was a landing on the nucleus of a comet to retrieve pristine material and return it to laboratories on Earth for detailed analysis.

As we shall see in the following chapters, the scientists’ dream encountered major obstacles, some of which proved to be insurmountable. However, even after the United States pulled out of the comet sample return venture, the ESA Member States decided to press ahead with their own remarkable comet chaser, soon named ‘Rosetta’. Despite further obstacles and setbacks, their foresight and commitment produced a truly historic mission.

This is the story of that monumental mission – the people, the hardware and the science that culminated in the unprecedented, close range exploration of a tiny chunk of ice and dust as it swept through space, hundreds of millions of kilometers from Earth. Its scientific results are revolutionizing our understanding of the billions of small, icy objects that populate the Solar System.

Peter Bond
June 2020

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Comets and Asteroids

> *When beggars die, there are no comets seen:*
> *The heavens themselves blaze forth the death of princes.*
> (Shakespeare's Julius Caesar)

By the late-1980s, all of the planets of the Solar System had been visited by spacecraft. However, in order to understand the formation and evolution of these worlds, including Earth, scientists were aware that they needed to study the small planetary 'building blocks' – comets and asteroids.

Inspired by the once-in-76-years return of Comet Halley, scientists from many nations began to propose new missions and instruments to explore these elusive chunks of rock and ice. In response to this demand, the European Space Agency (ESA) included a planetary cornerstone mission, subsequently named Rosetta, in its new, long-term Horizon 2000 science program.

Although the original plan to land on a comet's nucleus, retrieve samples of pristine material, and bring them back to Earth for analysis was eventually shelved, Rosetta survived as a mission to survey two main belt asteroids *en route* to a rendezvous with a periodic comet. After arrival, Rosetta would deploy a small lander on the nucleus and then fly alongside the comet to monitor changes in activity as it entered the inner Solar System and was warmed by the Sun.

This chapter is intended to put Rosetta's ambitious mission into context by describing what we knew of cosmic debris at the time that ESA's comet chaser began its 12-year adventure in March 2004.

P. Bond, *Rosetta: The Remarkable Story of Europe's Comet Explorer*,
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1.1 COSMIC DEBRIS

Earth is just one out of billions of planets that reside in an enormous spiral galaxy, the Milky Way. In one of the galaxy's spiral arms is an unremarkable star, the Sun, which lies at the center of our Solar System. It is accompanied by eight planets and a handful of dwarf planets, many of which have lesser companions orbiting around them. Less familiar are the swarms of cosmic debris that populate the seemingly empty spaces between the planets. Ranging in size from a few thousand kilometers across to mere specks of dust, these innumerable pieces of ice and rock represent the leftovers from the formation of the planets, some 4.5 billion years ago.

It is generally believed that the Solar System started with the collapse of an enormous cloud of interstellar gas. The trigger for this collapse could have been the passage of an externally generated shock wave from one or more exploding stars – supernovas – that occurred when giant stars in the cloud ran out of fuel and reached the end of their short lives.

Over millions of years, the original cloud may have broken up into smaller segments, each mixed with heavier elements from the dying stars, as well as the ubiquitous hydrogen and helium gas. Once a cloud reached a critical density, it overcame the forces associated with gas pressure and began to collapse under its own gravitational attraction.

The contracting cloud began to rotate, slowly at first, then faster and faster – rather like an ice skater who draws in her arms. Because material falling from above and below the plane of rotation collided at the mid-plane of the collapsing cloud, its motion was canceled out. The cloud began to flatten into a disk, with a bulge at the center where a protostar started to form. The disk could have been thicker at a greater distance from the evolving Sun, where the gas pressure was lower.

The solar nebula would almost certainly have been rotating slowly in the early stages, but as it contracted, conservation of angular momentum would have made it spin faster. This process naturally formed a spiral-shaped magnetic field that helped to generate polar jets and outflows associated with very young stars. Gravitational instability, turbulence, and tidal forces within the 'lumpy' disk may also have played a role in transferring much of the angular momentum to the outer regions of the forming disk.

The center of the protoplanetary disk was heated by the infall of material. The inner regions, where the cloud was most massive, became hot enough to vaporize dust and ionize gas. As contraction continued and the cloud became increasingly dense, the temperature at its core soared until nuclear fusion commenced. As a result, the emerging protostar started to emit copious amounts of ultraviolet

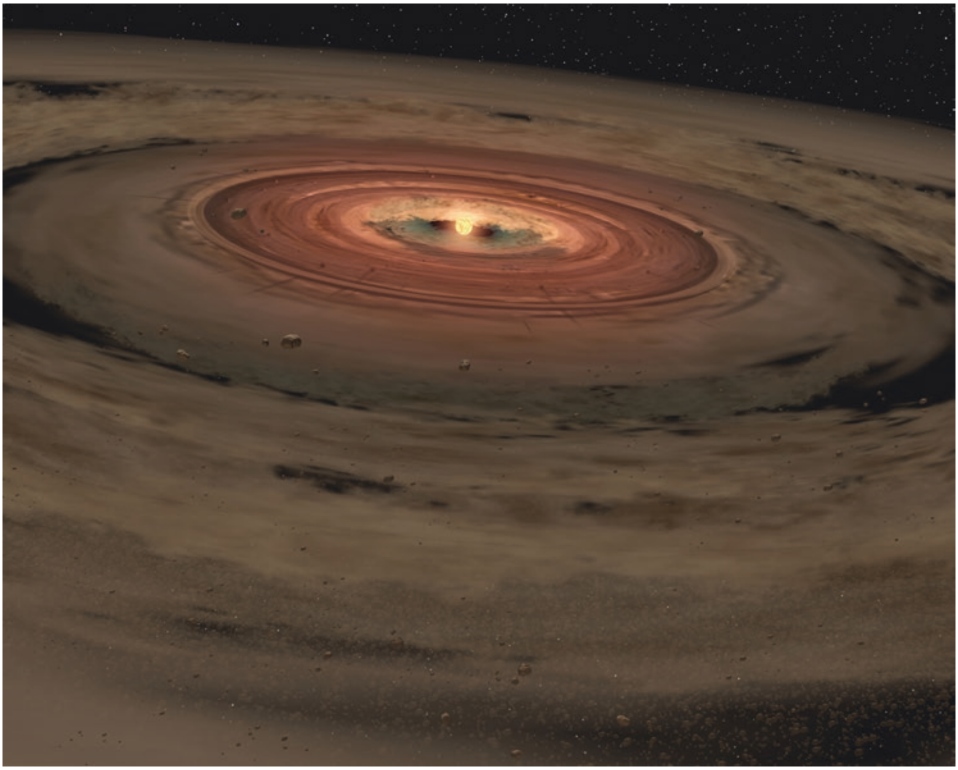

Fig. 1.1: Around 4.5 billion years ago, the infant Sun was surrounded by a rotating disk of dust and gas. Fledgling planets grew as the result of gravitational instabilities and turbulence within the disk, often followed by gigantic collisions. At the end of this process, smaller pieces of debris remained as rocky asteroids and meteorites, or icy comets. (NASA-JPL/Caltech/T. Pyle, SSC)

radiation. Radiation pressure drove away much of the nearby dust, causing the nebula to separate from its star.

The young star may have remained in this so-called T Tauri stage for perhaps 10 million years, after which most of the residual nebula had evaporated or been driven into interstellar space.[1] All that remained of the original cloud was a rarefied disk of dust grains, mainly rocky silicates and ice crystals.

Meanwhile, the seeds of the planets began to appear within the nebula. Rocky, less volatile material condensed in the warm, inner regions of the nebula, while icy grains condensed in the cold, outer regions.

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[1] T Tauri is a variable star in the constellation of Taurus and is the prototype of the T Tauri stars.

Individual grains collided and stuck together, growing into centimeter-sized particles. These swirled around at different rates, partly due to turbulence and partly due to differences in the drag exerted by the gas. After several million years, these small accumulations of dust or ice grew into kilometer-sized planetesimals and gravitational attraction took over.

The Solar System now resembled a shooting gallery, with objects moving at high speed in a chaotic manner, giving rise to frequent collisions. Some high speed impacts were destructive, causing the objects to shatter, generating a lot of dust or meteoritic debris. Slower, less violent collisions enabled the planetesimals to grow via a snowballing process. Over time, the energy loss resulting from collisions meant that planetary construction became the dominant process.

Eventually, the system contained a relatively small number of large bodies or protoplanets. Over millions of years, these continued to mop up material from the remnants of the solar nebula and collided with each other, producing a small population of widely separated worlds that occupied fairly stable orbits and traveled in the same direction around the young central star.

The largest planets in the Solar System – Jupiter and Saturn – probably formed first. They presumably accumulated their huge gaseous envelopes of hydrogen and helium prior to the dispersal of the solar nebula.

The small, rocky planets formed in the warmer, inner regions of the Solar System, whereas the gaseous and icy giants originated in the outer reaches. Observations of young star systems show that the gas disks that form planets usually have lifetimes of only 1 to 10 million years, which means that the giant gas planets probably formed within this brief period. In contrast, the much smaller, rocky Earth probably took at least 30 million years to form, and may have needed as long as 100 million years.

Theorists believe that for a while the outer planets interacted in a chaotic way, due to mutual gravitational interactions. Jupiter and Saturn may well have migrated inward before reversing direction. Farther from the Sun, the ice giants Uranus and Neptune may also have swapped places.

Vast numbers of small, leftover pieces of rock and ice avoided being swept up during this planet-building process. Any pieces of debris approaching too close to the giant planets would have been deflected either inward, toward the Sun, or outward, into the frigid depths. Some would even have been ejected from the Solar System completely.

Much of the rocky debris was shepherded into the asteroid belt that lies between the orbits of Mars and Jupiter. The overwhelming gravitational influence of Jupiter prevented this material from coalescing into a single planet, so its largest inhabitant, dwarf planet Ceres, has a modest diameter of 965 km; much smaller than Earth's Moon.

Much of the icy debris was removed to a region we now know as the Edgeworth-Kuiper Belt, lying just beyond the orbit of Neptune, 30 to 100 times Earth's distance from the Sun.[2] As a convenient metric for the Solar System, Earth's average distance from the Sun of about 150 million km is known as 1 astronomical unit (AU). Since 1992, dozens of objects, each several hundred kilometers across, have been discovered in this outer belt, as well as many thousands of smaller objects. Dwarf planet Pluto is its largest known member.

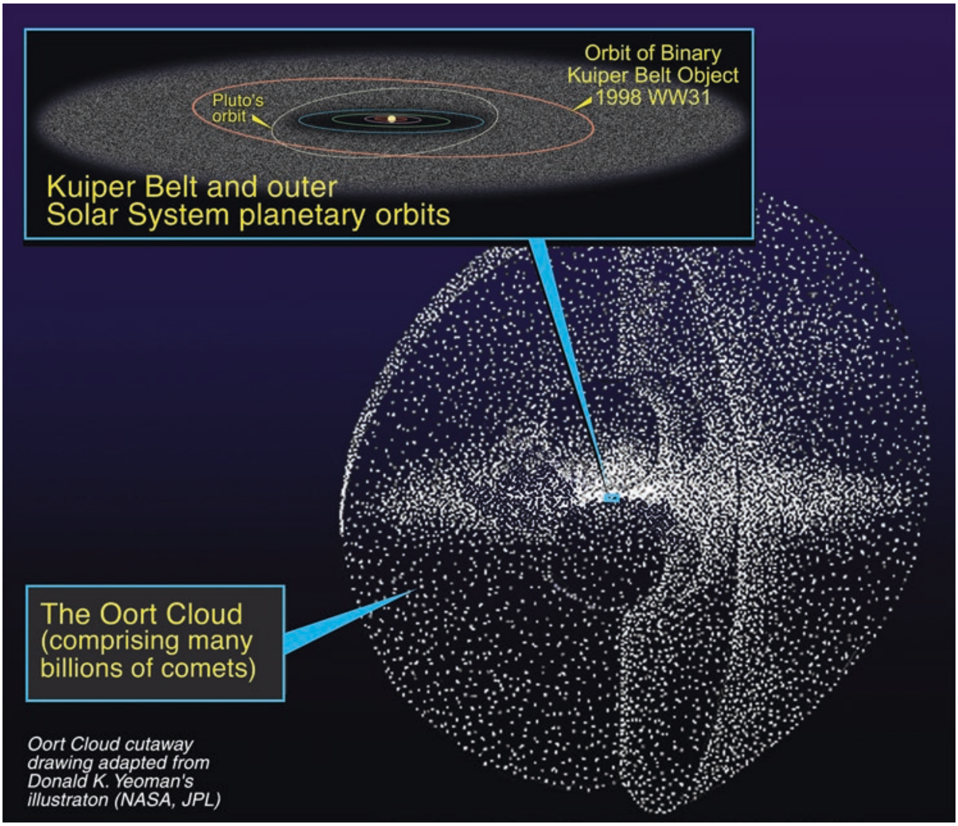

Fig. 1.2: The Oort Cloud is a spherical swarm of icy bodies 2,000 to 100,000 AU from the Sun. The diagram shows its presumed size and shape in relation to the Kuiper Belt and the region inside Pluto's orbit. (STScI/A. Field)

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[2] It is named after two astronomers, Kenneth Edgeworth and Gerard Kuiper, who independently suggested the existence of a swarm of comets beyond the orbit of Neptune. The name is usually abbreviated to Kuiper Belt. Much further from the Sun is the Oort Cloud, whose existence was first proposed by Dutch astronomer Jan Oort.

Many billions of icy objects were also ejected even farther, to the so-called Oort Cloud, a vast spherical region that is believed to lie between 2,000 and 100,000 AU.

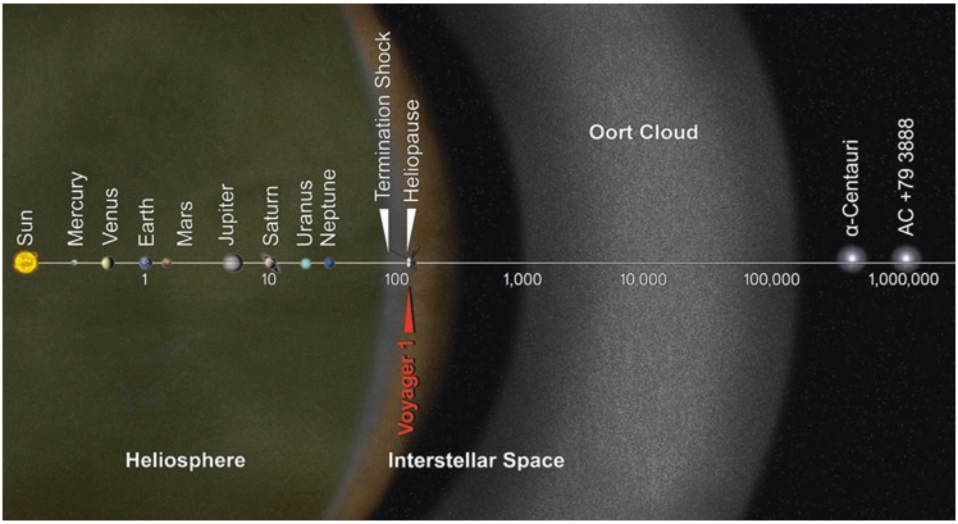

Fig. 1.3: The scale of the Solar System in units of AU, showing the planets, the Kuiper Belt, the Oort Cloud, and two nearby stars. (NASA)

By tracking the orbits of incoming comets, it is possible to determine where they came from. Comets that have fairly short period orbits – less than 200 years – originate in the Kuiper Belt. Those with much longer periods, often taking many thousands of years to orbit the Sun, come from the Oort Cloud. These were ejected into their extremely elliptical or parabolic orbits by gravitational interactions with the young gas giants. This process also scattered objects out of the ecliptic, the plane of Earth's orbit, producing a spherical distribution of the icy population.

Comets and asteroids (together with asteroid fragments known as meteorites) provide clues to the processes that led to the formation of the planets, some 4.5 billion years ago. But comets are the more useful objects for investigating the primordial Solar System. Whereas asteroids formed in the environment between the orbits of Mars and Jupiter, comets formed in the frigid regions much farther out and because their material is much less processed it is much closer to the pristine composition of the early Solar System.

1.2 LONG-HAIRED STARS

Comets are small, ice-rich objects which are most notable for sprouting long tails of gas and dust when their volatiles are vaporized in approaching the Sun. Every year, dozens of comets travel through the inner Solar System, passing close to the

Sun and then returning to whence they came. Most are not visible without the aid of binoculars or a telescope, but, occasionally, a very bright comet may blaze a trail across the night sky.

For thousands of years, these brilliant naked-eye comets have inspired awe and wonder – as anyone who saw the blue gas tail and yellowish dust tail of Comet Hale-Bopp in 1995 or the spiraling tails of Comet C/2006 P1 (McNaught) can testify.

Fig. 1.4: Comet Hale-Bopp, discovered by Alan Hale and Thomas Bopp on 23 July 1995, was one of the 'great comets' of the 20th century. As it approached the Sun from the Oort Cloud, it became extremely bright and active, developing a bluish ion tail some 8 degrees long and a yellowish dust tail 2 degrees long. The nucleus was estimated to be 35 to 40 km in diameter, which is huge compared with most comets that reach the inner Solar System. (ESO/Eckhard Slawik)

Many ancient civilizations saw these sudden apparitions as portents of death and disaster, and omens of social and political upheavals. Shrouded by luminous comas with tails streaming behind them, these ‘long-haired stars’ were assigned the name ‘comets’ by the ancient Greeks (from their word ‘kome’ meaning ‘hair’).

1.3 HALLEY AND PERIODIC COMETS

By the beginning of the 18th century, it was understood that comets were celestial objects that appeared without warning, illuminated the skies for several weeks or months as they moved closer to the Sun and then withdrew, presumably never to be seen again.

However, our understanding of the nature of comets was revolutionized by the British astronomer Edmond Halley (1656-1742). In 1705, when Halley began to calculate the orbits of 24 comets, he noticed that the path followed by a bright comet observed in 1682 was very similar to the orbits of other bright comets recorded in 1607 and 1531. He concluded the only reasonable explanation was that the same comet had reappeared over a period of 75-76 years. The slight variations in the timing of each return were attributed to small gravitational tugs on the comet by the giant planets.

Working forward in time, Halley predicted that the comet should return again in December 1758. Although he did not live to see the event, his theory was proved correct when the comet duly reappeared on schedule. The first periodic comet to be recognized was named 1P/Halley in his honor.[3]

Trawls through ancient records have revealed that this famous comet was recorded by the Chinese as long ago as 240 BC. It was later given a starring role in the Bayeux Tapestry – which told the story of the Norman Conquest of England in 1066 – and it may have inspired Giotto to include a comet in his 14th century painting, ‘Adoration of the Magi’.

Since Edmond Halley’s first successful prediction of a comet apparition, almost 400 periodic comets have been discovered and confirmed. They all follow recurring, elliptical orbits which last less than 200 years, but a large proportion of them have orbits that have been modified by close encounters with Jupiter, whose gravity dominates the Solar System.

Consequently, the farthest points of their orbits (aphelia) lie fairly close to the orbit of Jupiter, typically about 6 AU from the Sun. Each solar orbit takes about six years, although their paths are always being deflected by Jupiter and other planets. One of these Jupiter family comets is 67P/Churyumov-Gerasimenko, the target of Europe’s Rosetta mission (see Chapter 6).

The shortest period belongs to Comet 2P/Encke, which races around the Sun every 3.3 years. Some 150 known comets, including Halley’s, follow a more leisurely route, traveling beyond the orbit of Neptune prior to returning to the inner

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[3] The letter P after the number denotes a periodic comet.

Fig. 1.5: An image of Comet 1P/Halley taken on 8 March 1986 by W. Liller, as part of the International Halley Watch. Note the large dust tail and ion tail. (NASA/W. Liller)

Solar System. Although these comets have also been perturbed by encounters with the giant planets, their orbits are more random and are often steeply inclined to the ecliptic. Many of these, including Halley, travel in a retrograde direction.[4]

The orbits of periodic comets have evolved greatly since they were first formed. Comets with orbits of less than 200 years are believed to have originated in the Kuiper Belt, the doughnut-shaped region which ranges from the orbit of Neptune out at least 50 AU. They were probably ejected to their present location billions of years ago by gravitational interactions with Uranus and Neptune. Since the first Kuiper Belt Object was discovered in 1992, many hundreds more have been found.

As mentioned, the census of comets is increased when newcomers arrive from the depths of space, far beyond the Kuiper Belt. These intruders from the Oort Cloud, such as Hale-Bopp, appear without warning, moving along parabolic paths at high speeds. After sweeping rapidly around the Sun, they head back out, where they will remain for thousands of years.[5]

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[4] In terms of orbits, retrograde means ‘backward’ or clockwise when viewed from the north celestial pole.

[5] Occasionally, objects may enter our Solar System from interplanetary space. Traveling on hyperbolic paths, their velocities are so great that the Sun’s gravity cannot capture them. Two of these have been discovered in recent years.

1.4 DIRTY SNOWBALLS?

Although comets had been studied by ground-based telescopes for more than three centuries, we had little idea what they were made of, or where they came from, until the introduction of photography and the spectroscope.

The problem was that it is impossible to observe a comet's tiny nucleus from Earth. Even for the largest comets, such as Hale-Bopp, this icy heart measures only about 35 km in diameter. Furthermore, as soon as one of the wandering chunks of ice was close enough to make detailed observation, it was obscured by a coma of gas and dust. However, the growth of a coma and gas and dust tails as the nucleus was warmed by the Sun led to the reasonable hypothesis that the nucleus was a mixture of volatile ices and rocky material.

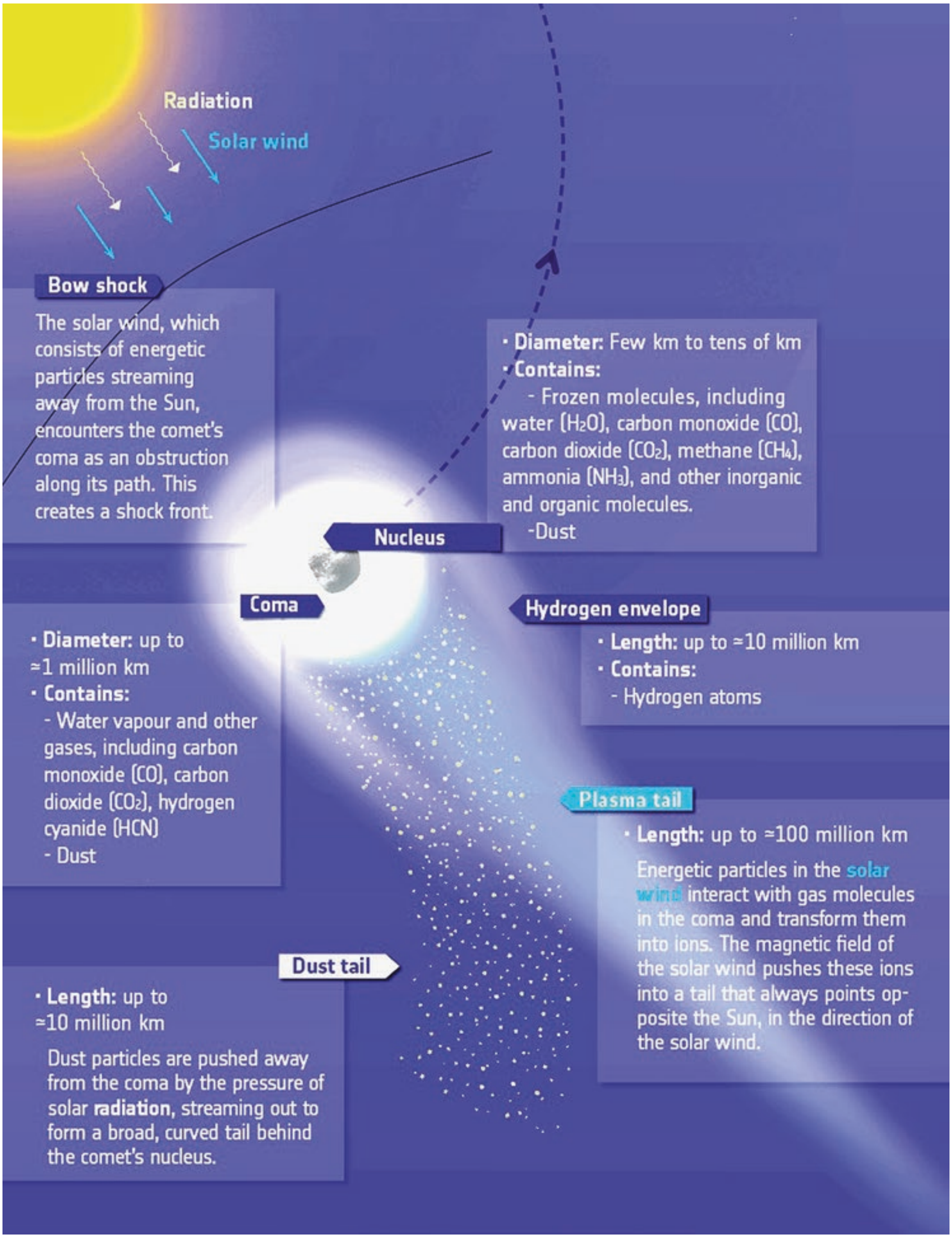
The key breakthrough came with the introduction of spectroscopy – a method of analyzing the light from the coma and tail. As early as the 1860s, the presence of compounds of hydrogen (H) and carbon (C) was revealed. Nitrogen (N) was also a common constituent.

Over the next century, spectral analysis of cometary gas revealed neutral molecules of CH (methylene), CN (cyanogen), and C_2 (carbon) beyond the orbit of Mars. Inside the orbit of Mars, the spectra included ionized (i.e. electrically charged) molecules (CO^+, N_2^+ and OH^+), along with CH_2 and NH_2. As the comets passed inside Earth's orbit, spectral lines for metallic elements such as sodium, iron and nickel began to be detected.

The most popular theory about the nature of comets was put forward in 1950 and 1951 by the American astronomer Fred Whipple, who is widely regarded as the 'grandfather' of modern comet science. Aware that some periodic comets must have made thousands of orbits around the Sun, he realized that they would have broken apart if they had comprised only a large pile of sand mixed with hydrocarbons.

Whipple concluded that comets were like dirty snowballs – large chunks of water ice and dust mixed with ammonia, methane and carbon dioxide. As the snowball approached the Sun, its outer ices started to vaporize, releasing large amounts of dust and gas that, in turn, formed the characteristic tails. He assumed that water vapor released from sublimating water ice was the main propulsive force behind the jets of material seen to originate on comet nuclei, but later data indicated that it is solar heating of frozen carbon dioxide beneath the surface that powers the jets of material that erupt from comet nuclei.

By the mid-1980s, when the Rosetta mission was being proposed, it was known that cometary nuclei were often amongst the blackest objects in the Solar System, despite their bright comas and tails. This is because the nucleus is coated in dark organic (carbon-rich) material, and dust is apparently thoroughly mixed with the ices inside. Scientists began to regard comets more as 'icy dirtballs' than 'dirty snowballs'.



Bow shock

The solar wind, which consists of energetic particles streaming away from the Sun, encounters the comet's coma as an obstruction along its path. This creates a shock front.

Nucleus

- **Diameter:** Few km to tens of km
- **Contains:**
  - Frozen molecules, including water (H_2O), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ammonia (NH_3), and other inorganic and organic molecules.
  - Dust

Coma

- **Diameter:** up to ≈1 million km
- **Contains:**
  - Water vapour and other gases, including carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN)
  - Dust

Hydrogen envelope

- **Length:** up to ≈10 million km
- **Contains:**
  - Hydrogen atoms

Plasma tail

- **Length:** up to ≈100 million km

Energetic particles in the solar wind interact with gas molecules in the coma and transform them into ions. The magnetic field of the solar wind pushes these ions into a tail that always points opposite the Sun, in the direction of the solar wind.

Dust tail

- **Length:** up to ≈10 million km

Dust particles are pushed away from the coma by the pressure of solar **radiation**, streaming out to form a broad, curved tail behind the comet's nucleus.

Fig. 1.6: The main features of a comet. (ESA)

Each time a comet approaches the Sun, it loses some of its material and mass. During its peak activity, near the Sun, Comet Halley was losing about 20 tonnes of gas and 10 tonnes of dust every second from seven jets of vaporized ice erupting from its nucleus.

Over time, a nucleus is depleted until all of its ices have been vaporized, at which point it may become inactive, resembling a small rocky asteroid. Alternatively, the comet might fragment into a swarm of dust particles.

Measuring the density of a nucleus is not easy, even by monitoring the trajectory of a nearby spacecraft, but estimates for various comets indicate they are typically 0.3-0.5 g/cm^3, which is considerably less than the density of water. This is probably due to a largely icy composition in combination with a porous, fluffy texture, or perhaps to a 'rubble pile' structure containing large voids.

Despite their insubstantial nature, their high impact velocity enables comets to cause a lot of damage if they collide with another object. Craters created by ancient comet and asteroid impacts can still be seen on the Moon, Mercury, Earth, and many planetary satellites.

In the case of Earth, only the largest nuclei survive to strike the ground and excavate a large crater. Most break apart in the atmosphere and explode in an enormous airburst that sends out shock waves in all directions. One of the most famous examples occurred on 30 June 1908, when an object, most likely a comet, exploded above the Tunguska region of Siberia and the blast flattened trees for a radius of hundreds of kilometers. If such an event were to take place above a conurbation such as London, the entire city would be flattened.

Fig. 1.7: This photo taken in 1927 shows parallel trunks of trees that were flattened by the shock wave from the 'Tunguska Event'. Note how the branches have been stripped off the trees. (ESA)

The most spectacular example of a comet collision occurred in 1994 when some 20 fragments of Comet Shoemaker-Levy 9 plunged into Jupiter, leaving a string of dark 'bruises' where the icy chunks exploded in the atmosphere.

Comets (and asteroids) may also have provided much of the water which now forms Earth's oceans, and possibly even delivered the complex organic chemicals that gave rise to the first primitive life forms.

1.5 TRANSIENT TAILS

Comets spend most of their lives far from the Sun, when they are invisible to even the largest instruments. However, any comet that enters the inner Solar System develops a shroud of gas and dust known as the coma. The roughly spherical coma is fed by jets of material that erupt into space as the surface of the nucleus is warmed by solar radiation.

The coma is mainly composed of water vapor and carbon dioxide. Some comas display the greenish glow of cyanogen (CN) and carbon when illuminated by sunlight. Other compounds of carbon, hydrogen and nitrogen have been found. Ultraviolet images by spacecraft have also shown that the visible coma is surrounded by a huge, sparse cloud of hydrogen gas.

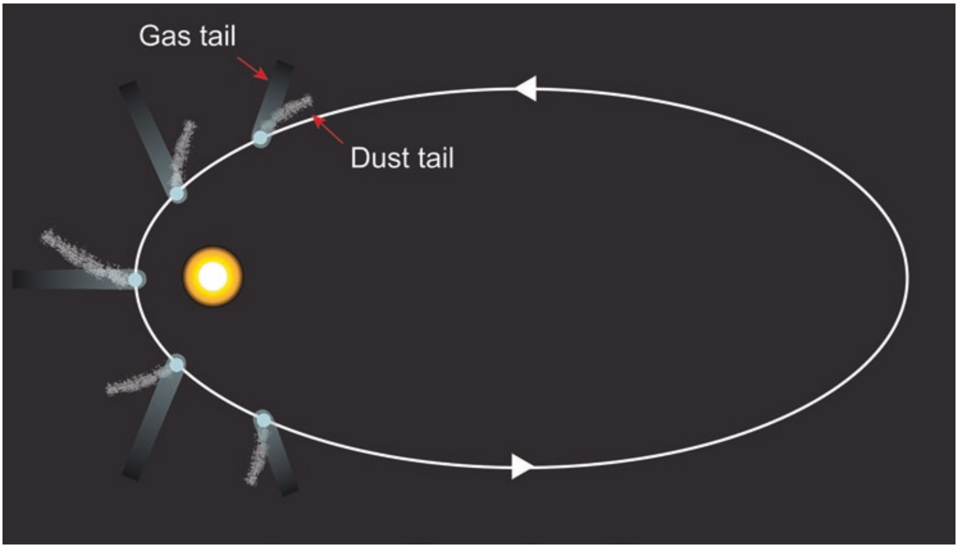


Fig. 1.8: Comets travel around the Sun in highly elliptical orbits, and when they venture into the inner Solar System the warmer environment causes volatiles in the nucleus to vaporize to produce a dense coma and tails of gas and dust. The tails always point away from the Sun. (Wikimedia https://en.wikipedia.org/wiki/Comet#/media/File:Cometorbit01.svg)

If the production of rates of dust and gas are sufficient, a comet can develop several tails. One is the yellowish dust tail. Usually broad, stubby and curved, these are formed when tiny dust particles in the coma are pushed away by solar radiation pressure, as photons of light impact the grains. Meanwhile, the gases released by vaporization of the nucleus are ionized by solar ultraviolet light. The ions are influenced by the magnetic field associated with the solar wind, a flow of electrically charged particles emanating from the Sun. The ions are swept out of the coma to produce a long, distinctive ion tail (also called a gas or plasma tail). Because the most common ion (carbon monoxide) scatters blue light better than red light, ion tails often appear blue to the human eye (see Figure 1.4).

Gusts in the solar wind can cause the ion tail to swing back and forth, sometimes developing temporary ropes, knots and streamers that can break away and then reform. These features are not seen in the dust tail. The ion tail is usually narrow and straight, often streaming away from the nucleus for many millions of kilometers. In 1998, analysis of data from the Ulysses probe indicated it had passed through the ion tail of Comet Hyakutake at the remarkable distance of 570 million km from the nucleus.

Fig. 1.9: Comet C/2006 P1 (McNaught) provided a spectacular sight close to the horizon in the southern hemisphere in January and February 2007. At least three jets of gas and small dust particles were seen to spiral away from the nucleus as it rotated, stretching over 13,000 km into space. The larger dust particles, which were ejected on the sunlit side of the nucleus, followed a different pattern. They produced a bright fan, which was then blown back by the pressure of sunlight. (ESO/Sebastian Deiries)

One of the most characteristic features of a comet's tail, is a shift in its alignment as the comet pursues its orbit. The solar wind sweeps past a comet at about 500 km/s, shaping the tails and making them point away from the Sun, particularly the ion tail. As a result, on the outward leg of its orbit, the solar wind causes the tails of a comet to point ahead of it, not trail behind it.

In extreme cases, comets have been observed to lose their tails temporarily when subjected to strong gusts in the solar wind. In 2007, NASA's Stereo spacecraft observed the collision of a coronal mass ejection (CME) – a huge cloud of magnetized gas ejected by the Sun – and the tail of Comet Encke, which was cut in two. This was triggered by a process known as magnetic reconnection, when the magnetic fields around the comet and the CME were spliced together.

When Earth passes through streams of material that are strewn along comets' orbits, the tiny particles burn up on entering the atmosphere, creating short luminous trails known as meteors or 'shooting stars'. More than twenty major meteor showers occur around the same time each year (see Table 1.1), with the shooting stars appearing to radiate from a point in the sky, like the spokes of a wheel.[6]

Table 1.1: Major Meteor Showers

Shower	Dates	ZHR*	Parent Comet
Quadrantids	Jan 1-6	100	96P Macholz 1?
Lyrids	Apr 19-25	10-15	C/1861 G1 Thatcher
Eta Aquarids	Apr 24-May 20	50	1P Halley
Delta Aquarids	Jul 15-Aug 20	20-25	96P Machholz 1?
Perseids	Jul 25-Aug 20	80	109P Swift-Tuttle
Orionids	Oct 15-Nov 2	30	1P Halley
Leonids	Nov 15-20	100	55P Tempel-Tuttle
Geminids	Dec 7-15	100	Asteroid 3200 Phaethon

*Approximate zenithal hourly rate

One of the best known showers is the Orionids, whose peak occurs in October. This stream of debris originated from Halley's Comet and the meteoroids penetrate the Earth's atmosphere at 237,000 km/h, which is faster than every other major annual shower apart from the Leonids in November. The Leonids are associated with dust from Comet 55P/Tempel-Tuttle. When that comet approaches the Sun, the Leonids can be spectacular. The displays from the apparitions in 1833 and 1966 produced over 100,000 meteors an hour.

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[6] Sporadic meteors may also appear at any time and from any direction throughout the year.