1

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.

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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

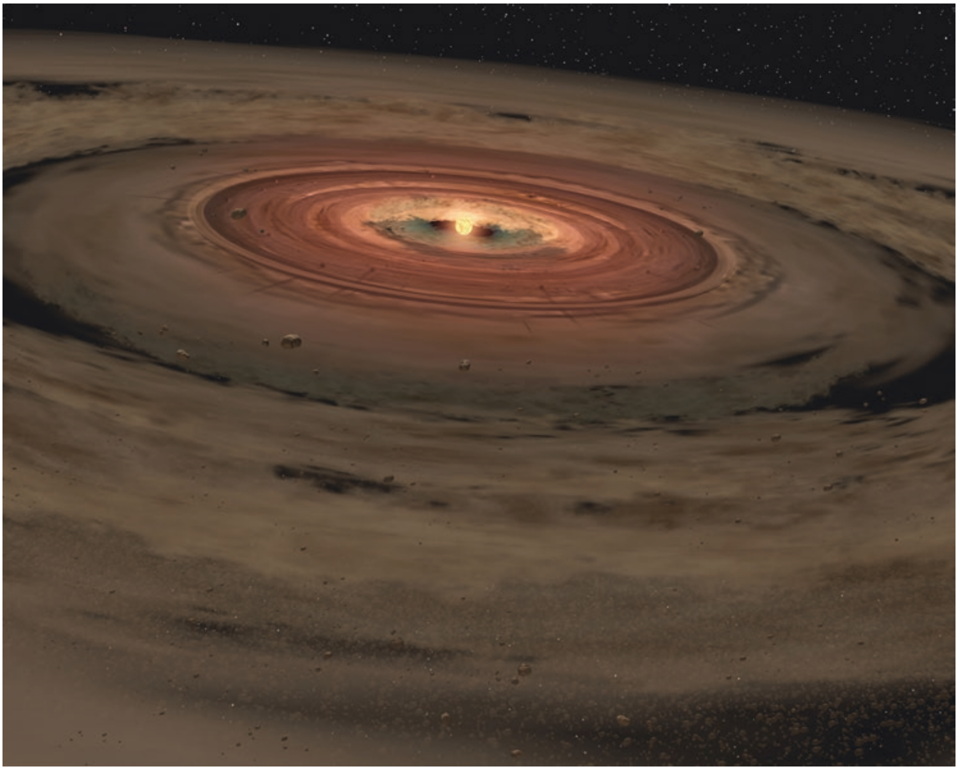

Fig. 1.1: Around 4.5 billion years ago, the infant Sun was surrounded by a rotating disk of dust and gas. Fledgling planets grew as the result of gravitational instabilities and turbulence within the disk, often followed by gigantic collisions. At the end of this process, smaller pieces of debris remained 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.

[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.

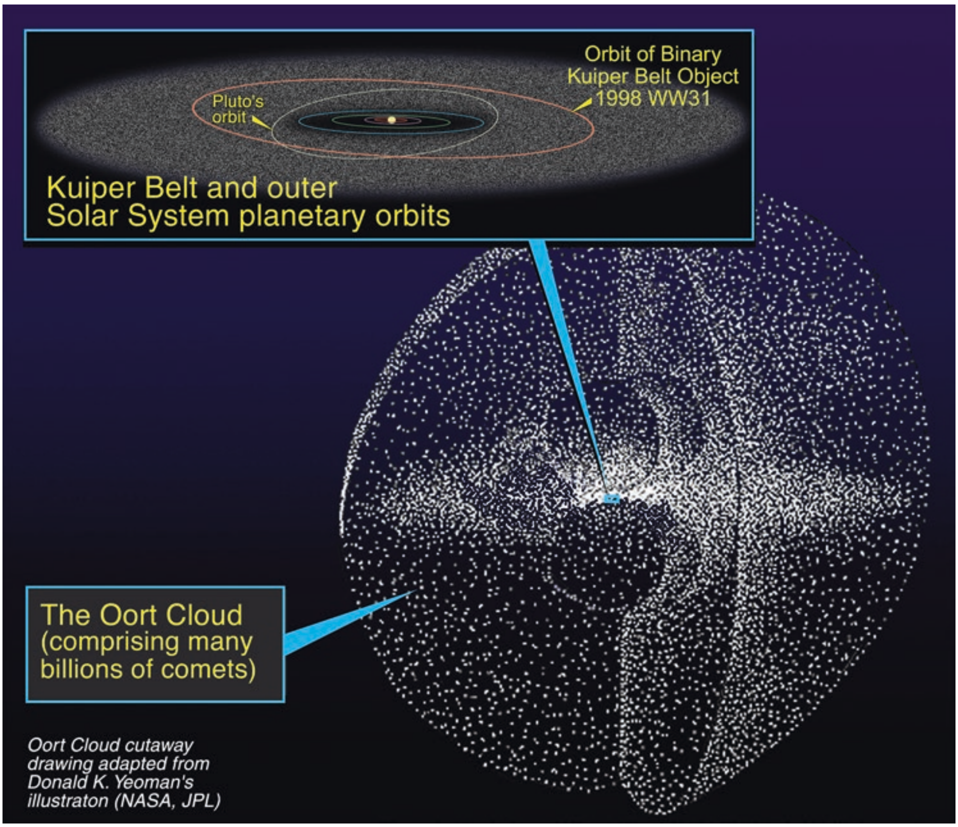

Fig. 1.2: The Oort Cloud is a spherical swarm of icy bodies 2,000 to 100,000 AU from the Sun. The diagram shows its presumed size and shape in relation to the Kuiper Belt and the region inside Pluto's orbit. (STScI/A. Field)

[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.

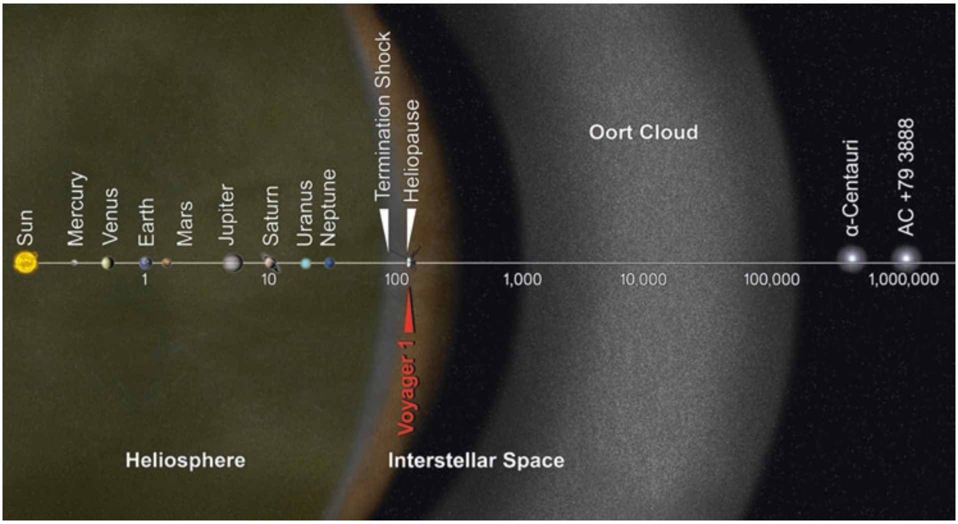

Fig. 1.3: The scale of the Solar System in units of AU, showing the planets, the Kuiper Belt, the Oort Cloud, and two nearby stars. (NASA)

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

[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'.

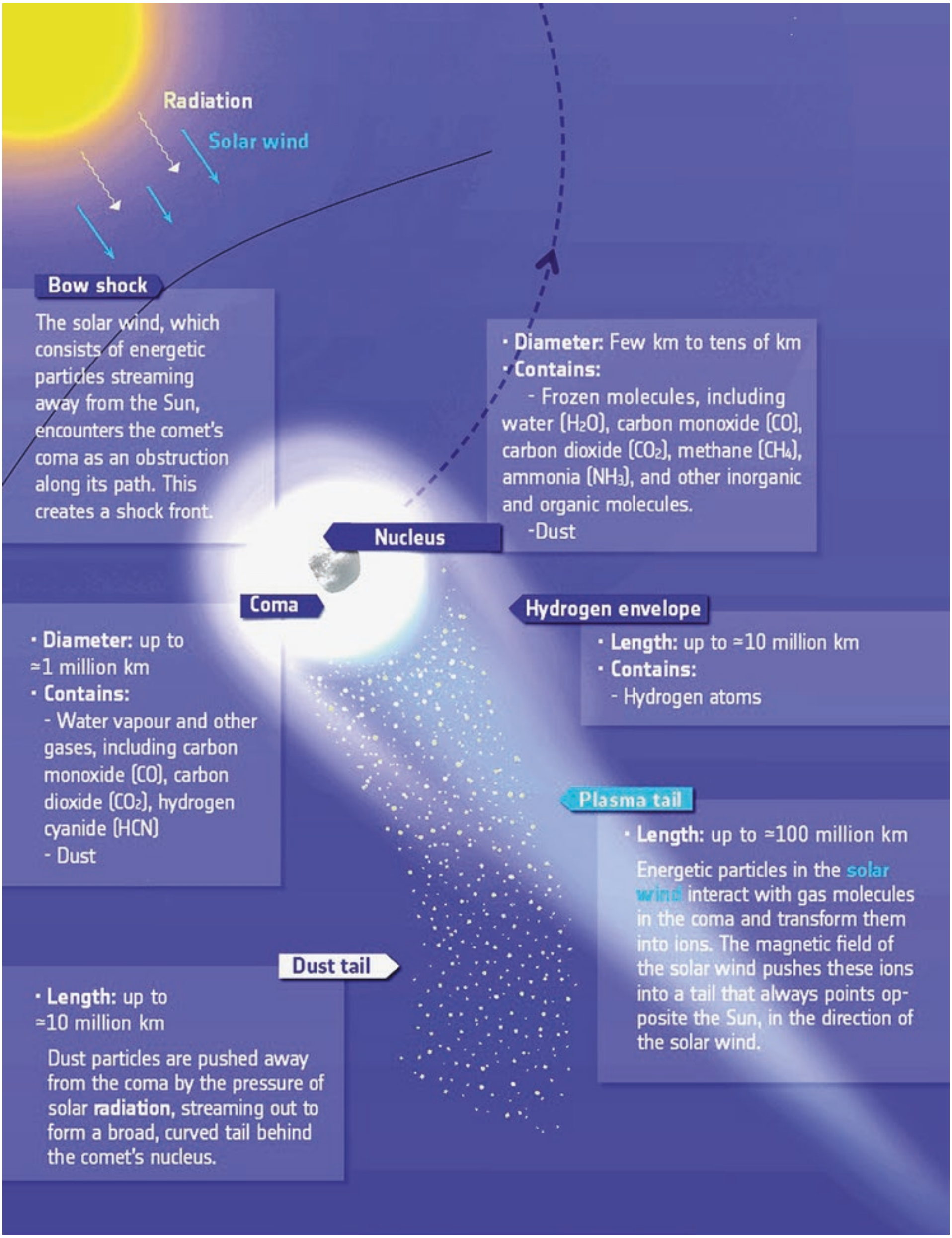

Fig. 1.6: The main features of a comet. (ESA)

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.

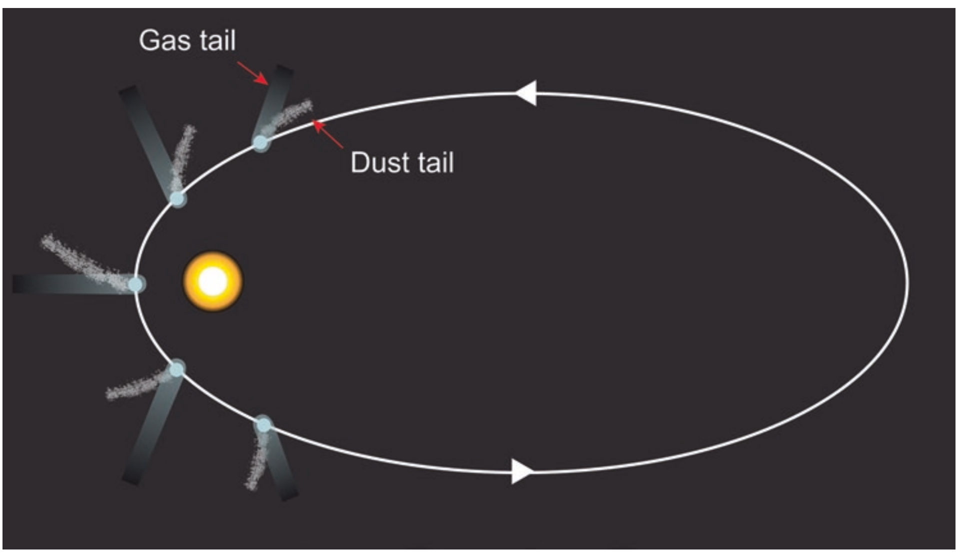

Fig. 1.8: Comets travel around the Sun in highly elliptical orbits, and when they venture into the inner Solar System the warmer environment causes volatiles in the nucleus to vaporize to produce a dense coma and tails of gas and dust. The tails always point away from the Sun. (Wikimedia https://en.wikipedia.org/wiki/Comet#/media/File:Cometorbit01.svg)

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.

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

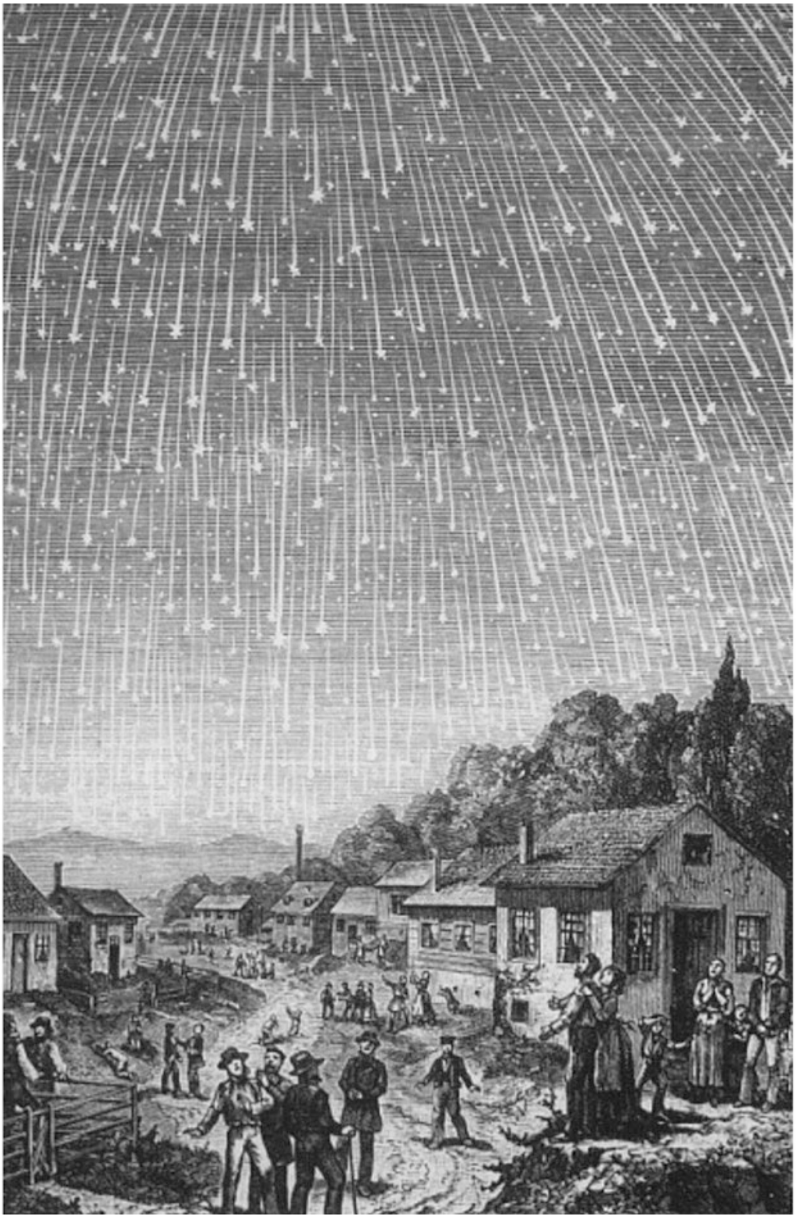

Fig. 1.10: This drawing shows the famous Leonid meteor storm of 12 November 1833, when the skies over the United States were ablaze with shooting stars. It was, one eyewitness said, as if "a tempest of falling stars broke over the Earth… The sky was scored in every direction with shining trails and illuminated with majestic fireballs." (ESA)

Sometimes Earth passes directly through a comet's tail, as happened during the apparition of Comet Halley in 1910. Many people were alarmed, since it was known that the tail contained cyanide (CN), a highly poisonous gas. But despite the doom-laden prophecies, the event had no noticeable effects. This was hardly surprising, since the tails of comets are so insubstantial that it is possible to observe stars through them. It was rather like hurling a bowling ball into a cloud of cigarette smoke.

1.6 BREAKING UP IS EASY TO DO

As long as they remain in the frigid depths of the Solar System, where temperatures plummet to –230°C, comets can survive intact for billions of years. But when they are nudged toward the Sun their nuclei can become susceptible to disruption. The fragility of a nucleus, owing to its porous or fractured nature, was indicated by objects that split into several pieces and often failed to reappear at their next expected return.

Comet 73P/Schwassman-Wachmann 3 began to splinter in 1995, during one of its numerous ventures into the inner Solar System. Shortly after experiencing a major outburst of activity, it split into four nuclei. The comet subsequently disintegrated into dozens of fragments. Hubble Space Telescope images indicated a hierarchical destruction process was taking place as large pieces continued to break up. Dozens of 'mini-fragments' were observed trailing behind each main object.

Occasionally, close encounters with planets can have a similar effect. One famous example is Comet Shoemaker-Levy 9, which was pulled apart by the tidal forces of Jupiter's tremendous gravity in 1992, forming a chain of around 20 pieces that crashed into the planet in July 1994.

An even more catastrophic example was Comet LINEAR (C/1999 S4), which disintegrated on 25 July 2000 during its first passage through the inner Solar System. Having appeared completely normal, the comet rapidly evolved into a fuzzy, extended, and much fainter object. By early August, all that could be seen of it was a cloud of debris, with no sign of the nucleus or any active fragments larger than a few meters across. It seemed that rapid vaporization near perihelion had caused the small nucleus to run out of ice, and with nothing to bond the solid material together it started to fall apart, leaving behind a loose conglomerate of particles that dispersed into space.

Comet nuclei can also be broken up by rapid rotation, thermal stresses as they pass near the Sun, or explosive disruption caused by trapped gases under pressure suddenly breaking out.

One example was Comet 17P/Holmes, which exploded on two separate occasions, firstly in November 1892 and again then in October 2007 as it approached the asteroid belt. During its 2007 apparition it unexpectedly changed from magnitude 17 to 2.8, thereby becoming almost a million times brighter in only 42 hours

Fig. 1.11: This Hubble Space Telescope image, obtained on 27 January 2016, reveals Comet 332P/Ikeya-Murakami disintegrating as it approaches the Sun. The main nucleus (lower left) measures about 490 meters across. The debris, visible near the center of the image, comprises a cluster of about 25 pieces, roughly 20-60 meters wide. They form a 4,800 km long trail of fragments that is drifting away from the comet. At that time, the comet was 240 million km from the Sun, slightly beyond the orbit of Mars. The small comet seems to be breaking up as jets of material erupting from the nucleus speed up its rate of rotation. (NASA, ESA, and D. Jewitt/UCLA)

and enabling it to be observed by the naked eye. The gradually expanding coma eventually grew larger than the Sun before finally dissipating.

Infrared observations in November 2007 by the Spitzer Space Telescope revealed a lot of fine silicate dust. This was apparently created by a violent explosion that destroyed larger particles in the interior of the nucleus. Calculations indicated the energy of the blast to be equivalent to 24 kilotons of TNT, and the total mass of the ejected material to be about 10 million tonnes.

The presence of jets and a spherical cloud (and particularly two similar events more than a century apart) indicated a collision was an unlikely reason. Thermal stresses are also unlikely to have been the cause, as in both cases the comet was well past perihelion and heading away from the Sun. It appears the nucleus acted like a pressure cooker, with trapped gases suddenly erupting through weaknesses in the surface.

Some comets undergo violent eruptions far beyond the warmth of the Sun. Perhaps the most impressive was the discovery on 15 February 1991 that Halley's

Comet was surrounded by a coma at least 300,000 km in diameter. This indicated a tremendous outburst. At the time, the object was 14.3 AU from the Sun, so this renewed activity was explained as sublimation of a more volatile compound than water, perhaps carbon monoxide or carbon dioxide, which built up sufficient pressure beneath the dark crust to trigger a major outburst.

1.7 VERMIN OF THE SKIES

Throughout most of recorded history, scientists and astrologers thought there were six planets (including Earth) in the Solar System. No one dreamt that there might be other worlds beyond Saturn, but there were occasional suggestions of one or more objects lurking unseen between the planets. Johannes Kepler, the 17th century mathematician who made a major advance by formulating the laws of planetary motion, was one who believed that another world must exist between Mars and Jupiter.

Then, in 1772, the German astronomer Johann Bode drew attention to a simple arithmetic progression which matched the distances of the planets from the Sun fairly accurately.[7] This so-called Bode's Law involved the series 0, 3, 6, 12, 24, and so on. Each successive number after 3 was double the previous number. After adding 4 to each number and dividing by 10, the sequence gave a good approximation to the actual distances of the known planets in units of AU (see Table 1.2).

Table 1.2: The Titius-Bode Law

Planet	Bode's Distance	Actual Distance from Sun (AU)
Mercury	0.4	0.39
Venus	0.7	0.72
Earth	1.0	1.0
Mars	1.6	1.52
(Ceres)	2.8	2.76
Jupiter	5.2	5.20
Saturn	10.0	9.53
Uranus	19.6	19.19
Neptune	38.8	30.06

Nine years later, in 1781, William Herschel in England discovered the planet Uranus more or less where the Titius-Bode Law predicted it ought to be. This

[7] Bode failed to mention that this mathematical curiosity had first been pointed out six years earlier by Johann Titius!

'confirmation' of the arithmetic progression encouraged others to search for new worlds.[8]

In 1800, a group of six astronomers, headed by Johann Schröter, gathered in the German town of Lilienthal with the intention of beginning a systematic search for a planet whose orbit lay at Bode's empty location of 2.8 AU, between the orbits of Mars and Jupiter. Their plan was to search the ecliptic, because the orbital planes of all the known planets were closely aligned to this. They divided it into 24 sectors, each of which was to be carefully scanned by a different observer. However, before the 'celestial police' could start their grand survey, some exciting news arrived from Sicily.

On 1 January 1801, Giuseppe Piazzi, director of the Palermo observatory, had discovered a mysterious, star-like object wandering among the stars of the constellation of Taurus. Initially he presumed it to be a comet, but the absence of a gaseous coma soon prompted doubts.

Unfortunately, on 11 February, Piazzi became seriously ill, and by the time he had recovered, the mysterious object had disappeared in the Sun's glare. With only limited information to go on, frustrated astronomers all across Europe began a frantic search for the mysterious object.

The breakthrough came when a brilliant young mathematician, Carl Gauss, devised a way of predicting planetary positions from a limited set of observations. Using Gauss's calculations, Franz Xavier von Zach, a member of Schröter's team, relocated it on 31 December, just half a degree from where Gauss had predicted.[9]

To everyone's delight, the newcomer was in an almost circular, planet-like path between the orbits of Mars and Jupiter. Piazzi suggested the name Ceres, the Roman goddess who was the patron of Sicily, which was soon adopted. Its distance from the Sun of 2.77 AU was an almost precise match for the empty 2.8 AU slot in Bode's Law. The one concern was that at only 8th magnitude Ceres had to be very small, more of a minor planet than a fully-fledged member of the Sun's family.

Then, on 28 March 1802, Wilhelm Olbers (another member of the 'celestial police') found a second object at Bode's distance of 2.8 while searching for comets. It was in an eccentric and inclined orbit. Named Pallas, it appeared to be even smaller than Ceres.

It was clear that these minor planets were rather different from their larger neighbors. Having noticed that they lacked planet-like disks even through his largest telescope, William Herschel suggested that they be collectively called

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[8] The relationship was not infallible. Neptune, which was only discovered in 1846, does *not* coincide with the predicted number. However, the dwarf planet Pluto orbits quite close to location 38.8.

[9] For comparison, the disk of the Moon is half a degree in diameter.

'asteroids' due to their star-like appearance. Olbers suggested they were remnants of a larger body that had exploded.

Further possible fragments were discovered by Karl Harding (an assistant of Schröter) in 1804 and by Olbers in 1807. Named Juno and Vesta, they were smaller than Pallas. The orbit of Vesta did not even approach those of the other three asteroids.

The scattered family seemed complete for nearly 40 years until a fifth minor planet (Astraea) was found in 1845, followed by three more in 1847. Since then, at least one asteroid has been discovered each year, with a marked increase in the discovery rate following the introduction of photographic techniques in the late 19th century.

Asteroids came to be regarded as small, unimportant rocky objects of little scientific interest. They appeared as unwanted trails on long photographic exposures, causing one astronomer to dub them "the vermin of the skies".

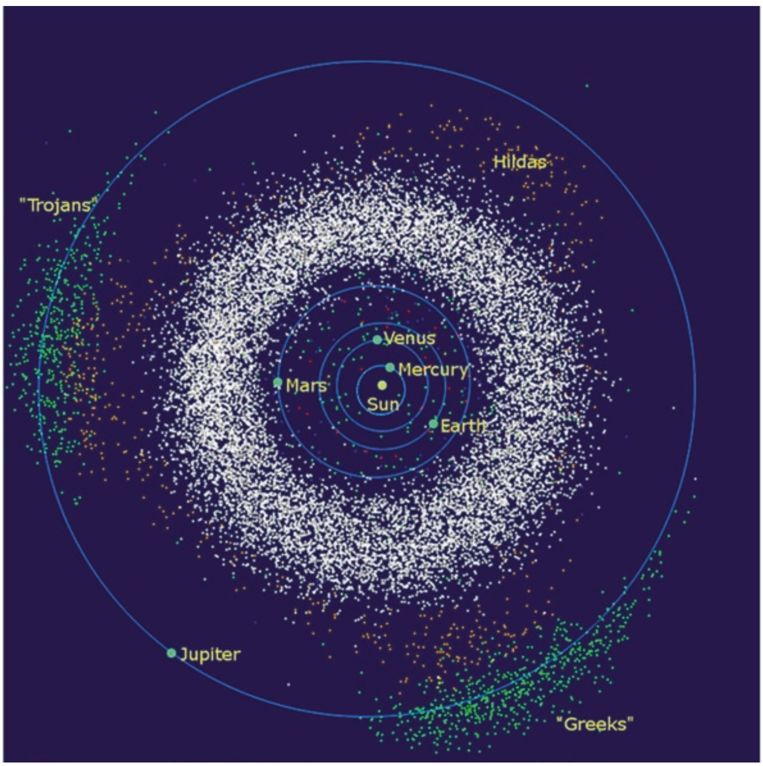

Fig. 1.12: The vast majority of the asteroids travel around the Sun in the main belt (white) in the gap between the orbits of Mars and Jupiter. The two 'clouds' of objects (green) which are centered 60 degrees ahead of and behind Jupiter in its 12 year orbit, are dubbed the Trojans and the Greeks. Also shown are the Hildas (orange) and some asteroids that approach (and in some cases cross) Earth's orbit. (Wikimedia https://en.wikipedia.org/wiki/Asteroid#/media/File:InnerSolarSystem-en.png)

Most of the asteroids proved to orbit the Sun between Mars and Jupiter, a region termed the main asteroid belt. In the early 20th century, two large groups of asteroids, collectively known as Trojans, were found to share Jupiter's orbit, on average leading it by 60 degrees and trailing it by 60 degrees.

Although most astronomers lost interest in the thousands of seemingly unimportant lumps of rock in the broad zone between the four terrestrial planets and their giant, gaseous cousins, the discovery of (433) Eros, the first of the so-called near-Earth asteroids, in 1898, caused quite a stir. As subsequent discoveries would establish, there are thousands of potentially hazardous objects capable of striking Earth (see The Impact Threat below).

1.8 ASTEROIDS

With a diameter of 970 km, Ceres, the biggest member of the asteroid belt, is large enough to have achieved an almost spherical shape. It accounts for about 25% of the overall mass of the belt. A handful of other asteroids are also nearly spherical, but the vast majority are small and irregular in shape.

Asteroids that have been visited by spacecraft or imaged using ground-based radar are often double-lobed. Those with two components in contact at a narrow waist were evidently formed when separate asteroids gently collided and became gravitationally bound.

However, many asteroids appear to be very weak internally, rather like clumps of rubble that are loosely held together by gravity, and they may be readily broken apart by more energetic collisions. Even an increase in their rotation rate may be sufficient to break them asunder.

Close binaries are quite common, with two objects circling their common center of gravity. A few triples have also been discovered. Many of the meteorites arriving on Earth are thought to have originated from the shattering of asteroids (see Meteorites below).

Asteroids have been classified according to the spectra of their reflected sunlight. The most common are the C-type of carbon-rich or carbonaceous asteroids. They are more numerous in the middle and outer regions of the main belt. They are very dark and black-brown in color.

The next most common group is the S-type of stony or silicaceous objects that are composed of metal-rich silicates. These predominate in the inner main belt, at solar distances of less than 2.4 AU. They reflect more light than the C-types.

The third most populous group is the M-type of metallic asteroids. These are believed to be derived from the nickel-iron cores of objects which were large enough to melt internally and then differentiate, with the denser metals sinking

Fig. 1.13: Asteroids vary considerably in composition, shape and size. Top left: The S-type (433) Eros measures 33 × 13 × 8 km. Top right: The C-type (253) Mathilde is 59 × 47 km, and is darker than asphalt. Images from the NEAR spacecraft by NASA-JPL. Center right: Diamond-shaped (162173) Ryugu is a C-type asteroid less than 1 km wide. Bottom left: The peanut-shaped S-type near-Earth asteroid (25143) Itokawa is 535 × 294 × 209 meters. Images from the Hayabusa project by JAXA.

toward the center. When such objects were broken apart by violent collisions, some of the resulting asteroids were fragments of the metal cores. Based on its reflectance spectrum, asteroid (21) Lutetia, one of the targets of the ESA Rosetta mission, was either a C-type or an M-type.

Many other types and subtypes are recognized. For example, the other asteroid target for the Rosetta mission, (2867) Steins, was classified as a rare E-type object, based on its high albedo (reflectivity) and its visual and near-infrared spectral characteristics.

1.9 METEORITES

Every day, about one hundred tons of interplanetary material drifts down to Earth's surface. Most numerous are the tiny dust particles that are released by comets as their ices vaporize in the solar neighborhood. However, larger pieces of rock also arrive from deep space and some of these survive to reach the surface in the form of meteorites.

Most meteorites come from the main asteroid belt, between Mars and Jupiter. The first clear evidence of this link between asteroids and meteorites came in 1959, when scientists were able to photograph an incoming meteorite with sufficient accuracy to calculate its orbit. Since then, many other meteorites have been traced back to the asteroid belt.

In the 1980s, scientists recognized that a few rare meteorites found on Earth have been ejected by impacts on the Moon and Mars. These provide invaluable information about the chemical composition of the Solar System, past and present, and they help scientists to understand the composition and nature of the interstellar cloud in which our star and planets were born.

The most common meteorites are stony, some are metallic, some are mixtures of stone and metal, and a few fragile specimens are rich in carbon. The type of meteorite is related to the type and size of the asteroid that was its parent.

The iron-rich meteorites are derived from the molten cores of large asteroids that were at least several tens of kilometers across. The heat came from radioactive decay of elements and large impacts with other objects.

The core formed where denser material sank toward the center, whereas silicate rock rose to create a less dense, rocky crust. Material of intermediate buoyancy produced the mantle. This process is known as differentiation.

Iron meteorites are made of varying proportions of iron and nickel alloys. Their existence is evidence of the catastrophic destruction of large, differentiated M-type asteroids by collisions.

Stony-iron meteorites are thought to have originated at the core-mantle boundary inside large asteroids. Stony meteorites were formed either in undifferentiated

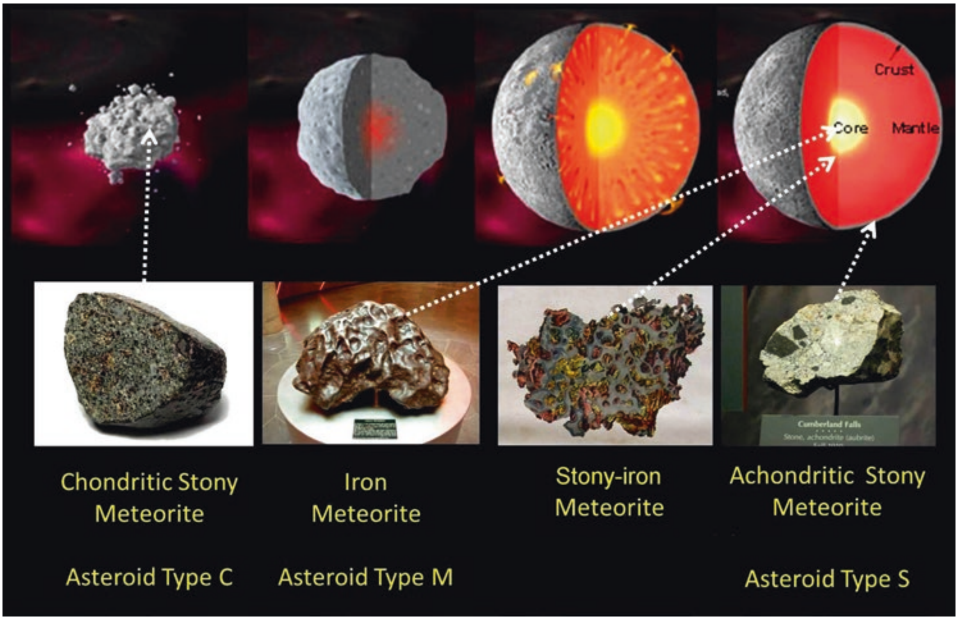

Fig. 1.14: When an asteroid or a protoplanet accretes sufficient material, it begins to become roughly spherical in shape. Heat from radioactive decay of elements and numerous collisions causes melting. In a process known as differentiation, the densest, metal-rich material sinks to the core, and the lightest rock floats to the surface. The type of meteorite derived from one of these asteroids depends on the part of the asteroid where it originated. (After the Smithsonian Museum of Natural History)

objects or at the surface of a differentiated asteroid, where constant impact bombardment caused the rocks to be mixed. Primitive stony meteorites are called chondrites because they contain spherical grains known as chondrules, which consist of silicates and are typically about 1 mm in diameter.

1.10 THE IMPACT THREAT

As the numbers of known near-Earth objects steadily grew, awareness of the potential threat spread beyond the scientific community and, in 1994, the U.S. Congress gave NASA the task of discovering, within a decade, 90% of all near-Earth objects (NEOs) larger than 1 km in size. The impact of such an object could cause global-scale devastation sufficient to send humanity the way of the dinosaurs.

Fig. 1.15: On 28 February 2009, Peter Jenniskens, an astronomer at NASA Ames Research Center and the SETI Institute in California, found two pieces of the 2008 TC3 asteroid, an SUV-sized object that broke apart over the Nubian Desert of northern Sudan in 2008. This was the first time scientists had the opportunity to study meteorites definitively linked to a particular asteroid that exploded on entering the atmosphere. (NASA/SETI/P. Jenniskens)

To follow this up, Congress issued a new challenge in 2005 by instructing NASA to discover 90% of NEOs with diameters larger than 140 meters by 2020. Their estimated average impact rate is about 10,000 years, which equates to a 1 in 100 chance every 100 years.

Although considerably less destructive than a 1 km impactor, such an object would be capable of destroying a large city, laying waste to a country-sized area, or producing a tidal wave that would inundate low lying coastal areas.

Although they are much more numerous, NEOs in this more modest size range are not easy to detect or to characterize, because most of them are spotted

Fig. 1.16: Meteor Crater (also called Barringer Crater) in Arizona, is one of the most recent impacts on Earth. It was created about 50,000 years ago when an iron meteorite excavated a hollow about 1.2 km wide and 180 meters deep. Surrounding the basin is a wall of material 30-45 meters high where the target rock was uplifted and, in some cases, overturned. The 30 meter wide meteorite probably weighed about 100,000 tons and struck the surface at a speed of around 12 km/s. The energy released was equivalent to about 2.5 megatons of TNT. (D. Roddy/USGS, Lunar and Planetary Institute)

only when they pass close to Earth. To date, only about 40% of the smaller members of this group have been found, together with around 80% of the larger members.

Meanwhile, every month small chunks of rock fly within a few Earth-Moon distances of our planet, with the possibility that, at some time in the future, they will collide with Earth. At the time of writing (in 2020) 2,018 of these potentially hazardous objects had been detected.

The detection of as many NEOs as possible, and the determination of their orbital paths, sizes, shapes and compositions will be essential if we are to avoid a catastrophic impact, but there is not yet an accepted strategy for preventing such an event.

As dramatized in Hollywood blockbusters, the most obvious solution would appear to be to launch a missile carrying a nuclear warhead to break up a large asteroid. Unfortunately, this is likely to create a swarm of smaller objects that would continue on a similar course and cause multiple impacts across the world, delivering a similar total energy release. It would be rather like the fragments of Comet Shoemaker-Levy 9 colliding with Jupiter.

The less drastic alternative of deflecting an object from its collision course has been widely studied. In most cases, a change in orbital speed of several centimeters per second would be sufficient. Deflection methods generally call for either a sudden, fairly large lateral force, or a slow, relatively gentle, but prolonged thrust.

Once again, nuclear devices have been suggested because they can supply around a million times more energy per unit of mass than conventional explosives. Impacts by non-explosive projectiles have also been proposed.

A more subtle approach is the so-called 'gravity tractor', whereby the minuscule gravitational pull provided by a nearby thrusting spacecraft would very slowly accelerate the asteroid in the spacecraft's direction. Although the acceleration imparted to the asteroid would be very small, this method would be able to alter an asteroid's orbit slightly. Calculations show that a 20 ton gravity tractor could deflect a 200 meter asteroid after a year of such 'towing'.

Another innovative proposal involves placing an electromagnetic 'mass driver' on the surface of a NEO. Material excavated on the asteroid's surface would be fired into space, creating an equal and opposite reaction that adjusts the orbit. A similar concept involves anchoring either ion engines or a solar sail on an asteroid, in order to apply a weak propulsive force over a long period of time.

The need for the difficult task of anchoring such devices can be overcome if a solar sail or a mirror can be placed in orbit. By focusing incoming solar radiation onto the NEO, some of the surface would be strongly heated and vaporized, with the resultant jet of material adjusting its trajectory.

Whichever method is chosen, it should be borne in mind that a deflection mission could take years to develop and another 5 years to reach its target. Furthermore, the propulsive procedure itself may require many years to have the desired effect. Hence the threat must be recognized well in advance.

1.11 WHY STUDY COSMIC DEBRIS?

As the innumerable impact craters on our Moon demonstrate, Earth has been bombarded by comets, asteroids and meteorites for billions of years. Although the storm has abated in more recent times, there are close encounters on a weekly basis. At least once per century, an object large enough to cause widespread damage, and possibly loss of life, enters the atmosphere and explodes, sending shock waves to the surface.

Most recently, on 15 February 2013, a 10-20 meter wide object exploded in the air above the city of Chelyabinsk in Russia. The blast injured about 1,500 people and damaged more than 7,000 buildings, collapsing roofs and breaking thousands of windows.

As mentioned above, there is little that we can do to avoid the fate of the dinosaurs unless we use our technology to mitigate the impact risk. One essential prerequisite is to catalogue all of the most threatening objects, so that we can prepare well in advance for their arrival from the depths of space and hopefully have time to take preventative measures.

Understanding their trajectories is necessary but not sufficient. We must also understand their physical properties: composition, density, size, and so on.

Comets and asteroids represent a diverse menagerie of ancient debris, ranging in size from less than one kilometer to hundreds of kilometers. Some are mainly composed of solid metal, most are stony, while others are friable and fragile. Some are comparable to fluffy snowballs, some are loose rubble piles, and others are dense, solid chunks of rock. Some are shaped like peanuts with two lobes separated by a waist, some are close binaries, a few are triple systems orbiting their common center of gravity.

Although ground-based observations will always play a role, the only way to achieve a true understanding of these objects is to visit them with spacecraft. To date, most of these missions have involved relatively short fly-bys that provided snapshots of the object over a period of a few days.

Now, however, a new era of intense examination is under way, with the first asteroid sample return missions such as Japan's Hayabusa series and NASA's OSIRIS-Rex. NASA and ESA are also planning a joint planetary defense mission that will examine a technique for changing the trajectory of an asteroid using a so-called kinetic impactor. The Deep Impact mission fired a projectile into a comet to investigate its composition. The NASA Stardust mission collected tiny samples of comet dust and returned them to Earth for study. (See Appendix 1 for a list of missions.)

The following chapters tell the story of the mother of all missions to explore cosmic debris, the ESA Rosetta 'comet chaser' that flew alongside the nucleus of a comet for two years and sent a lander down to its craggy surface.

REFERENCES

Exploring the Solar System (2nd edition), Peter Bond, Wiley-Blackwell, 2020
Minor Planet Center: https://minorplanetcenter.net/
Comets (NASA): https://www.nasa.gov/comets
Comets (NSSDC): https://nssdc.gsfc.nasa.gov/planetary/planets/cometpage.html
Comets: https://en.wikipedia.org/wiki/Comet
Asteroids (NSSDC): https://nssdc.gsfc.nasa.gov/planetary/planets/asteroidpage.html
Asteroids: https://en.wikipedia.org/wiki/Asteroid
Eight billion asteroids in the Oort cloud, Andrew Shannon et al: https://arxiv.org/pdf/1410.7403.pdf

List of Potentially Hazardous Asteroids (PHAs): https://www.minorplanetcenter.org/iau/lists/PHAs.html
Center for Near Earth Object Studies: https://cneos.jpl.nasa.gov/
Asteroid Watch (NASA-JPL): https://www.jpl.nasa.gov/asteroidwatch/
Asteroid Radar Research: https://echo.jpl.nasa.gov/
Meteoroids: https://en.wikipedia.org/wiki/Meteoroid
Meteorites: https://en.wikipedia.org/wiki/Meteorite