

Scientists are keenly interested in comets, because comets are "frozen time capsules" revealing important information about the early history of the Solar System.

I. Historical background

Comets have played a role in the history of science.

In the year 1577, a very bright comet appeared. According to the beliefs of the time (dating back to Aristotle) comets were thought to be phenomena in the Earth's atmosphere. The Danish astronomer Tycho Brahe reasoned that, if comets were indeed in the Earth's atmosphere, then observers at different sites should see a shift in the comets's position projected against the background stars (parallax). Tycho made careful observations of the comet's position relative to nearby stars (remember, this was in an era before the invention of telescopes). He compared his measurements with those of other observers at different locations in Europe. No parallax was evident, and Tycho concluded that the comet was at least 6 times as far away as the Moon, definitely not in the atmosphere!

It was left to Isaac Newton, a century later, to show that comets, like the planets, move in elliptical orbits under the influence of the sun's gravity. In fact, Newton's influential *Principia* might never have been published without Edmund Halley's persistence. Halley then used Newton's mathematics to work out the orbits of several previously observed comets (No computers or even hand calculators back then!). He noted that the comets seen in the years 1531, 1607, and 1682 had almost identical orbits and concluded it was the same comet with a period of 75-76 years. In 1705 he predicted its return in the year 1758. The comet did return as Halley had predicted (although he did not live to see it) and now bears his name. This successful prediction finally brought comets out of the realm of myth into the realm of science. The successful prediction also did much to popularize Newton's work and usher in the Age of Reason in European science and philosophy. (But most of the bright comets we can see without the aid of a telescope have periods of thousands of years or more.)

II. Anatomy of a Comet

We distinguish several parts of an active comet, with very different spatial scales.

1. Nucleus: 1-10 km diameter

The nucleus of a comet is composed of a mixture of ices, primarily water ice but also CO, CO₂, H₂CO (formaldehyde) and other ices at the 1% level, as well as rocky material: silicates and carbon-rich material of sizes from sub-micron to meters. The interior structure of a comet is not well understood, because we see only the material shed by a comet near the Sun. Indirect evidence suggests that the mean density is $< 1 \text{ g/cm}^3$ (1 g/cm^3 is the density of water ice, whereas silicate rocks have a density closer to 3 g/cm^3). So, we really don't know how strong the comet nucleus is. Some comet nuclei have been observed to split into 2 or more pieces, for example Comet Shoemaker-Levy 9, which was torn apart by Jupiter's gravity during a close

encounter in 1992 and the pieces crashed into Jupiter in 1994. The SOHO spacecraft has imaged over 600 comet fragments approaching the Sun, thought to be the remnants of a giant sun-grazing comet. Check out the SOHO website for images!

We have close-up views of just 3 comets, Halley, Borrelly, and Wild 2 imaged by spacecraft. These images show that comets have very dark (low albedo) surfaces, not what you would expect from ice. Also, the measured infrared radiation from the nucleus indicates surface temperatures of about 300 K, not what you would expect from an icy surface. An icy surface exposed to sunlight near 1 AU will sublimate. Most of the solar energy will be used for the sublimation and the surface temperature will be in the range 180-200 K, well below that of a black-body. (we call this sublimation-buffered temperature). The images also show that the gas and dust are being emitted only from small areas on the sunlit side of the nucleus.

We infer from these observations that the ices are not exposed right on the surface, but are embedded below the surface and the sublimating gases are emitted through vents or craters. The European Rosetta mission, targeted to rendezvous with a comet and monitor its activity throughout perihelion passage, will provide new information on this process.

2. Inner coma: $< 10,000$ km

Composed of molecules sublimated from the nucleus and small solid particles entrained in the outflowing gas. The molecules have not yet been photodissociated - we refer to them as "parent molecules". This region can best be explored from a spacecraft.

3. Outer coma: 10,000 - 100,000 km

Parent molecules are photodissociated; for example $\text{H}_2\text{O} \Rightarrow \text{H} + \text{OH}$. We see the molecular fragments, such as CN, C_2 , C_3 , NH, CH, OH in optical spectra. Solid particles with an aggregate structure may fragment and hydrocarbon components may be released from the grains as they heat up.

4. Hydrogen coma: 10^6 km

Water, the dominant molecule released from a comet nucleus, is dissociated by solar photons to form a huge expanding cloud of hydrogen gas. Since the fundamental electronic transition to the ground state of the hydrogen atom emits a photon in the ultraviolet (Lyman-alpha 1216 Å), this huge cloud was not detected until the first ultraviolet measurements from above the Earth's absorbing atmosphere.

5. Dust tail: up to 10^7 km

The dust tail is formed by small solid grains that move under the influence of solar radiation pressure. We can see the dust tail because of the sunlight scattered by the small grains. Spectra confirm that one is seeing continuum radiation, not individual gaseous emission lines. Each solid particle follows a trajectory determined by the vector sum of the comet's orbital motion, the outflow velocity given to it by the outflowing gas in the inner coma, and the solar

radiation pressure. Since the net force of radiation pressure relative to solar gravity depends on the ratio of the dust particle's cross section/mass, the smallest particles will have the highest velocity and the particles will spread out in the tail according to their size. Large particles are less influenced by solar radiation pressure and will disperse approximately along the comet's orbit, where they can be detected as a meteor shower if the Earth intersects the comet's orbit.

6. Ion tail: $10^7 - 10^8$ km

The ion tail, or plasma tail, is composed of molecular ions and electrons. Because these atomic particles are charged, they move under the influence of the magnetic field carried by the solar wind and are dragged away from the comet in a direction approximately radially outward from the sun.

III. Origin of comets

Comets formed at the same epoch as the planets, roughly 4.6 billion years ago, in the outer parts of the solar nebula, from about 5 AU (near Jupiter) to 50 AU. In these regions, the temperature was cold enough that water existed in the form of ice. That's very important, because water is one of the most abundant substances, composed of the Universe's most abundant element (H) and oxygen, one of the elements most abundant after H, He. The ices and bits of rocky material slowly accreted to form "icy planetesimals". These icy planetesimals had a varied history. Some were swept up into the giant planets, The remaining objects that were formed in the region of the giant planets had their orbits severely perturbed by Jupiter and the other giant planets: some were sent inward, where they impacted the terrestrial planets (did comets bring water and carbon compounds to the early Earth??) or fell into the Sun, some were ejected from the solar system altogether, and some eventually ended up in very long elliptical orbits, extending to the outer limits of the Sun's gravitational influence. This vast region from about 50,000 - 100,000 AU is known as the Oort Cloud and may contain a trillion (10^{12}) comets. Other icy planetesimals formed beyond the giant planets, from about 30 to 50 AU. This region is called the Kuiper Belt, or Edgeworth-Kuiper Belt. The largest (brightest) objects in the Kuiper Belt have been detected only within the last decade.

The comets we see today come from two reservoirs: Long-period comets come from the Oort Cloud, whereas short-period comets with prograde, low-inclination orbits (Jupiter family comets) originate from the Kuiper Belt. In both cases, the comets have been parked in "cold storage" since the early epoch of the solar system. While the larger objects of the solar system have undergone substantial thermal alteration, comets have not. Thus, comets carry a frozen record of the chemical composition of the solar nebula. And solid grains in the original interstellar cloud from which the sun and planets formed could have been preserved and incorporated into comet nuclei essentially intact - grains that are older than the solar system! Comets are truly ****frozen time capsules****.

Moreover, during the era of heavy bombardment at the end of planet formation, comets impacting the Earth may have brought substantial amounts of water to form the Earth's oceans (still a controversial, but not unlikely idea) as well as complex carbon-based molecules that could serve as building blocks for the first life forms.

IV. Space missions to comets

Although there is much we can learn about comets remotely, primarily via spectroscopy, there are some science questions that can only be answered by direct sampling. Comet missions include flybys, rendezvous, and sample return. A flyby through the coma can sample directly the composition of the gases and can take a census of the mass distribution and elemental composition of the solid particles. The European Giotto mission to comet Halley in 1986 was a very successful flyby. Images of the nucleus can also be acquired from a flyby, as in the Giotto flyby of Halley and the DS-1 flyby of Borrelly (<http://nmp.jpl.nasa.gov/ds1/>).

But this is only a snapshot of a comet at one moment in time and does not tell us much about the physical processes of cometary activity. These can best be learned from a rendezvous, a spacecraft that flies with the comet along its orbit and observes the products of the comet's activity over many weeks/months. The European Rosetta mission, launched in early 2004 after many delays, will rendezvous with a short-period comet in the next decade. (<http://sci.esa.int> click on Missions, select Rosetta)

Finally, we would like to bring a sample of cometary material back for analysis in the laboratory, where powerful modern techniques can be applied to analyze samples on a microscopic scale, techniques that could never be miniaturized to fly on a remote spacecraft, with its mass, space, power, and data rate limitations. Ultimately, we would like a frozen sample of the interior of a comet nucleus. However, a first - and much less complex - step is a sample of the solid debris shed by a comet into the coma. The first such mission is STARDUST!

V. STARDUST Mission www.stardust.jpl.nasa.gov

STARDUST is a comet flyby sample return mission selected by NASA as the 4th Discovery mission. The primary objective is to capture an intact sample of the solid particles (dust) shed by a comet and return the sample to Earth for detailed compositional analysis in modern laboratories.

The sample collector consists of a grid of aerogel rectangles, measuring 2 x 4 cm area and 3 cm thick, for a total collecting area of about 0.1 m². The sample collector extends on an arm, which can be folded up inside an aerodynamic capsule for the return trip and ultimate descent through the Earth's atmosphere. Aerogel is an extremely low density material designed to slow down and capture microscopic particles (size < 100 μm) within a range of 3 cm (for the largest particles). The aerogel we are flying actually has a graded density, from 5-10 mg/cm³ on the front surface to 50 mg/cm³ at the back. (Note that's milligrams/cm³, compared with the density of water, 1 gram/cm³). Intact capture has been proven in the laboratory and on experiments capturing particles in Earth orbit.

In addition to the sample collector, the spacecraft carries a small navigation camera necessary to target within 300 km of the nucleus. A set of dust impact detectors completes the payload. These detectors will give us a rough idea of how much dust has been captured and the mass distribution of the dust (small vs. large particles).

Comet P/Wild 2 is a short period comet (only short period comets have their orbits known well enough to target a spacecraft accurately!) that probably originated in the Kuiper Belt beyond the orbit of Neptune.

While the spacecraft was enroute to the comet, the back side of the aerogel collectors (cubes 1 cm thick, 20 mg/cm³) was exposed at certain times in an attempt to collect pristine interstellar grains moving through the solar system. Thus, in a single mission, we hope to capture ancient interstellar grains frozen into the comet 4.6 billion years ago and modern interstellar dust. Hence the name of STARDUST for our mission!

The spacecraft was launched February 7, 1999. After 4 long years cruising in interplanetary space, the spacecraft sped past comet P/Wild 2 at 6 km/sec on January 2, 2004, passing within about 240 km of the nucleus. The miss distance of 240 km was a compromise between the desire to approach as closely as possible to collect as much dust as possible vs. the concern about the possible presence of large particles, > 1 cm, that could damage the spacecraft. The spacecraft is protected by a 2-layer "bumper shield" on the leading edge. The first layer is actually a series of thin sheets designed to fragment and/or vaporize incoming hypervelocity particles up to 1 cm in size. The second, thicker layer is designed to stop these fragments and debris cloud. No large impact was detected and there is no known damage to the spacecraft resulting from the flyby.

The navigation camera acquired a spectacular set of images, over a range of angles as the spacecraft sped past. These images show a very battered old object a few km in diameter, covered with covered with craters, pits, and depressions reflecting its 4.5 billion year history cruising around the solar system. The surface looks different from any other small object yet seen in the solar system (e.g., asteroids, small moons). From pictures alone, it is difficult to distinguish between features due to impacts and those caused by sublimation and subsequent erosion. We can say that the surface must have strength, because there are vertical features 100 m high. Some of the images were deliberately overexposed to bring out the jets of material emitted from the nucleus. Dust impact detectors mounted on the front bumper shield detected bursts of tiny particles when the spacecrat penetrated these jets. For an analysis of the images, see Brownlee et al. Science, June 18, 2004. You can examine the images at the Stardust website, stardust.jpl.nasa.gov.

After the encounter, the collected sample was retracted and securely stowed in the return capsule for the 2-year trip home. The spacecraft will reach Earth and send the all-important capsule down through the atmosphere on January 15, 2006. The samples will be stored in clean room conditions at Johnson Space Center, and any scientists with the necessary analysis instrumentation can apply to receive a sample. We will be investigating their chemical composition, isotope ratios, mineralogy and the composition of any carbonaceous material.