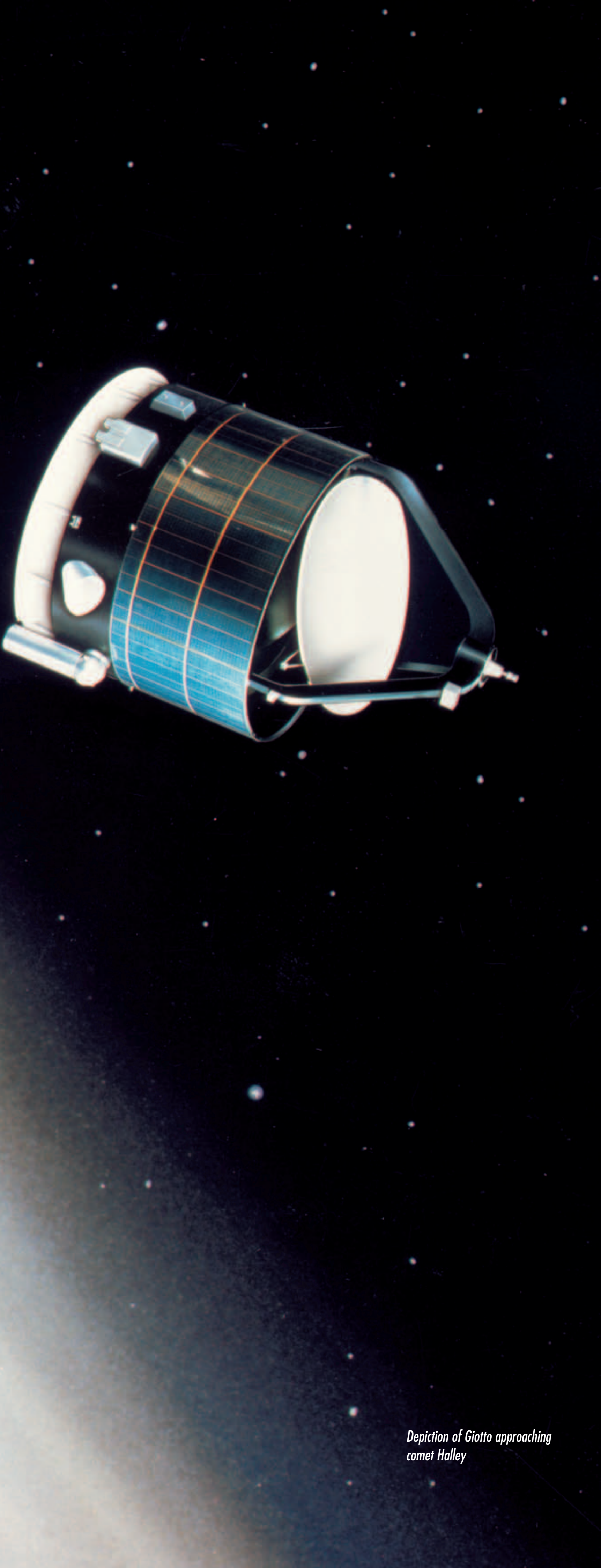
Twenty Years after Giotto

– ESA's Pioneering Mission to Comet Halley



Depiction of Giotto approaching comet Halley

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Almost exactly twenty years ago, on 14 March 1986, ESA's Giotto spacecraft made its historic fly-by of comet Halley at a distance of about 596 km. This close encounter represented a major milestone for planetary science in general, but also gave an important boost to the European planetary-science community that is still having an impact today. Besides its scientific importance, it was also the first big mission-related media event for ESA. The 'Night of the Comet' at ESOC in Darmstadt (D) was relayed by Eurovision, with 56 TV stations from 37 countries reporting the encounter live, attracting a television audience of more than 1.5 billion. The images sent back by Giotto's Halley Multicolour Camera radically transformed everyone's ideas about what the nucleus of a comet really looked like.

After the successful tours of NASA's Pioneer and Voyager spacecraft through our Solar System with their close fly-bys of the outer planets, an encounter with a comet was perhaps the last but one truly exploratory mission left in terms of Solar System studies. The last one, the New Horizons mission to study Pluto from close quarters, has only just been launched on 20 January this year. Interestingly enough, like Giotto, it is again exploring an 'icy body' and thereby probing the early stages of the evolution of our planetary system.

Before the Giotto mission, very little was known about the most active and most primitive members of our Solar System; for example, we could only speculate about the existence and size of the cometary nucleus, which becomes active when it approaches the Sun. Heated by insolation, the nucleus releases large amounts of gas and dust during the comet's passage through the inner Solar System. The gas streaming away from the nucleus carries with it large quantities of fine dust, which is responsible for much of the comet's visual brightness. The gas and dust form the coma and the characteristic gas and curved dust tails of the comet.

Although we had large sets of ground-based observations of comets gathered over many centuries at our disposal, our real knowledge before the Halley encounters was still very limited and only in-situ measurements, even with a simple fly-by mission, could provide answers to a number of fundamental questions, such as:

– Is there a nucleus at the centre of the comet?
– What are the size, shape, albedo, composition, surface temperature, rotation rate and rotational axis of the nucleus?
– Are there active regions on the nucleus?
– What are the parent molecules?
– Which chemical processes occur in the cometary coma?
– What are the dust and gas production rates?
– What is the dust size distribution?
– How big are the smallest dust particles?
– What is the composition of the dust particles?
– What are the abundances of the different molecules and ions making up the cometary atmosphere?

These and many other such fundamental questions drove the rationale for Giotto's in-situ exploration of comet Halley.

Still, twenty years later, one can claim that Giotto carried the most comprehensive and sophisticated payload to date with which to study a comet nucleus at close quarters. Only ESA's Rosetta mission, with its Philae Lander, will address a wider range of science when it reaches comet 67P/Churyumov-Gerasimenko in 2014, circles it and then follows it for a considerable fraction of its orbit – in another ten years from now!

Giotto Science Instruments
Halley Multicolour Camera (HMC)
CCD camera with f/7.68 Ritchey-Chretien telescope, 22 m resolution from 1000 km.13.5 kg, 11.5 W. PI: H.U. Keller, MPI für Aeronomie (D)
Neutral Mass Spectrometer (NMS)
Energy/mass of neutral atomic particles: 1-36 amu, 20-2110 eV. 12.7 kg, 11.3 W. PI: D. Krankowsky, MPI für Kernphysik (D)
Ion Mass Spectrometer (IMS)
Energy/mass of ions. 9.0 kg, 6.3 W. PI: H. Balsiger, Univ. of Bern (CH)
Dust Mass Spectrometer (PIA)
Mass ($3x10^{-16}$-$5x10^{-10}$ g) and composition (1-110 amu) of dust particles. 9.9 kg, 9.1 W. PI: J. Kissel, MPI für Kernphysik (D)
Dust Impact Detector (DID)
Mass spectrum of dust particles: 10^{-17}-10^{-3} g. 2.3 kg, 1.9 W. PI: J.A.M. McDonnell, Univ of Kent (UK)
Johnstone Plasma Analyser (JPA)
Solar wind and cometary ions 10 eV-20 keV, cometary ions 100 eV-70 keV/1-40 amu. 4.7 kg, 4.4 W. PI: A. Johnstone, Mullard Space Science Laboratory (UK)
Rème Plasma Analyser (RPA)
Solar wind and cometary ions 10 eV-30 keV, cometary ions 1-200 amu. 3.2 kg, 3.4 W. PI: H. Rème, Centre d'Etude Spatiale des Rayonnements (F)
Energetic Particles Analyser (EPA)
3-D measurements of protons (15 keV-20 MeV), electrons (15-140 keV), α-particles (140 keV-12.5 MeV). 1.0 kg, 0.7 W. PI: S. McKenna-Lawlor, St Patrick's College (IRL)
Magnetometer (MAG)
0.004-65 536 nT. 1.4 kg, 0.8 W. PI: F.M. Neubauer, Institut für Geophysik und Meteorolgie (D)
Optical Probe Experiment (OPE)
Coma brightness in dust and gas bands. PI: A.C. Levasseur-Regourd, Service d'Aeronomie du CNRS (F)
Radio Science (GRE)
Cometary electron content and mass fluence. PI: P. Edenhofer, Institut für Hoch- und Höchstfrequenztechnik (D)

Giotto's scientific payload consisted of 10 experiments weighing a total of approximately 60 kg: a camera for imaging the comet nucleus, three mass-spectrometers for analysing the elemental and isotopic composition of the cometary dust and gas, various dust-impact detectors, a photo-polarimeter for measuring the coma's brightness, and a suite of plasma instruments for studying the solar-wind/comet interaction.

Why Halley?

The most active and therefore the brightest comets are the so-called 'new' ones, which are entering the inner Solar System for the first time. Ideally then, one would like to organise an encounter with one of these comets, but with present-day technology this is impossible. To be able to plan a successful mission to a comet, its orbit must be well-known, which means that the comet must have 'returned' several times. This rules out new comets and leaves only the short-periodic and a few intermediate-period comets as potential candidates for investigation.

The preference for also visiting a well-known and very active comet left very little choice, and Halley, with its 30 recorded previous apparitions, proved to be the most logical target. It is the only one of more than 1000 catalogued comets that has a well-known orbit and a high gas and dust production rate. Comet Halley is also the most famous of all the comets. Although its fame was not the main factor in its selection, the prime reason for its choice, namely its brightness and its well-known orbit, are the very reasons for its fame. It is so bright in the sky and it reappears so regularly that it has been observed during each of its 30 apparitions since 240 BC. It was this comet that led Edmond Halley to his most important discovery of the periodicity of some comets.

The Encounter

The Giotto spacecraft was launched on 2 July 1985 by an Ariane-1 vehicle from Kourou in French Guiana. The ESA ground station at Carnarvon in Australia

The Giotto spacecraft installed on its Ariane-1 launcher in Kourou, French Guiana

was used for the spacecraft's operation, and CSIRO's 64 m radio-astronomy dish at Parkes (Australia) for the high-rate transmission back to Earth of its scientific data. During the encounter itself, NASA's 64 m Deep-Space Network station in Canberra (Aus.) was in 'hot standby'.

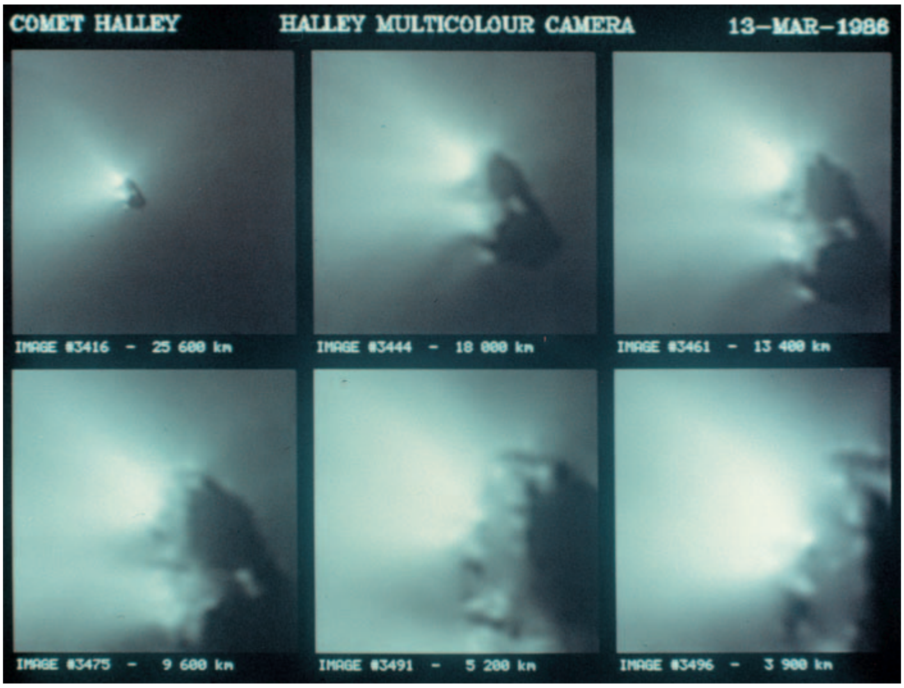
A few days before the encounter, the decision had to be taken regarding the spacecraft's closest approach distance to the nucleus. 500 ± 40 km was chosen as the best compromise between the requirements from the payload Principal Investigators for the camera, the instruments that wanted to pass as close as possible, but with a high chance of survival, and those who wanted to go as close as possible even if the spacecraft wouldn't survive the resulting dust impacts. All went well until about 14 seconds before closest approach, when a hit from a 'large', i.e. 0.1 - 0.2 gram, dust grain caused a nutation of the spacecraft. For about 32 minutes, the telecommunications link to Earth could not be maintained continuously and scientific data were received only intermittently. Thereafter, the spacecraft returned to its nominal operating mode and science data-taking was continued for another couple of days. It very soon became clear, however, that a few of the instruments had been severely damaged, namely the HMC, NMS, IMS-HERS, JPA-FIS and RPA (see table).

Nevertheless, for the Giotto spacecraft the journey wasn't over. On 2 April, it was put into a hibernation (safe) mode, and essentially powered down. Then, after nearly four years in this state of hibernation, the spacecraft was reactivated on 24 February 1990, retargeted to make an Earth fly-by on 2 July 1990 at a distance of 22 720 km (the first-ever gravity assist at Earth for a spacecraft coming from deep space) and, after a second hibernation period, reactivated again on 8 May 1992 to encounter its second comet, Grigg-Skjellerup, on 10 July 1992.

The Halley Armada

ESA wasn't the only space agency to send a spacecraft to Halley in 1986: the Soviet Vega-1 and Vega-2 spacecraft were launched on 15 and 21 December 1984, respectively; Japan's Sakigake was launched on 8 January 1985, and the second Japanese spacecraft, Suisei, was launched on 19 August 1985. Although these launch dates were spread over a period of eight months, all of the encounters with Halley occurred within a week of each other in March 1986: 6 March for Vega-1 at 8890 km from the comet, 8 March for Suisei at 151 000 km, 9 March for Vega-2 at 8030 km, and 11 March for Sakigake at 7 million km, 14 March for Giotto, and 25 March for NASA's ICE at 28 million km.

The space agencies involved had realised several years earlier that many aspects of mission planning, spacecraft and experiment design, and data evaluation were common to all missions, and that the overall scientific return could be increased through cooperation. They therefore agreed in 1981 to form the Inter-Agency Consultative Group for Space Science (IACG), which had the task of informally coordinating all matters related to their missions to comet Halley and the observations of it from space. Perhaps the most visible achievement of the IACG was the improvement of Giotto's targeting accuracy through the Pathfinder Concept. Giotto was last to make its fly-by and could use information about the position of the nucleus obtained by the cameras onboard the Vega-1 and Vega-2 spacecraft to improve its targeting accuracy. NASA supported this effort by reducing the Vega



Giotto returned more than 2000 images during its fly-by of comet Halley. The six shown here range from 375 seconds (#3416) to 55 seconds (#3496) before closest approach (Courtesy of H.U. Keller, MPS)

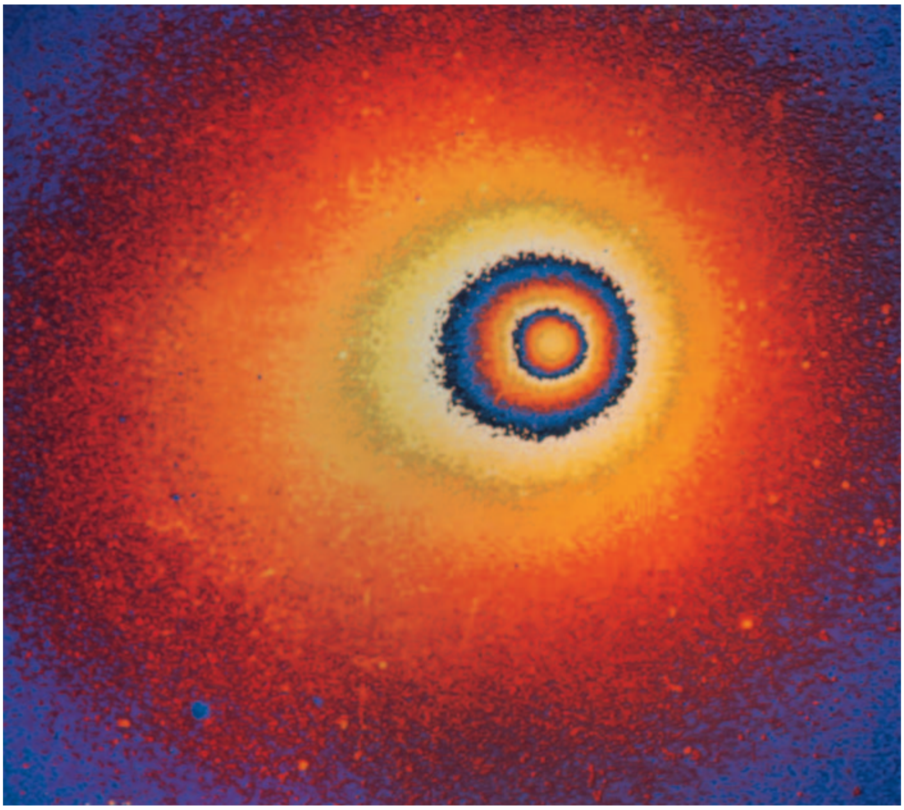
positioning uncertainty to about 40 km using Very Long Baseline Interferometry techniques with the widely separated tracking stations of its Deep Space Network.

The other big international effort was the IHW (International Halley Watch), which complemented the in-situ observations made by the various experiments carried by the six fly-by spacecraft with remote observations from the ground and from space. It was a huge international network that brought together both professional and amateur astronomers around the World to monitor the target comet in all of its different aspects, including the development of the dust and gas coma, the plasma tail dynamics and, especially for Giotto, astrometric observations to improve the knowledge of the ephemeris. The wealth of data collected through the efforts of the IHW helped to put the spacecraft in-situ observations into the proper scientific context.

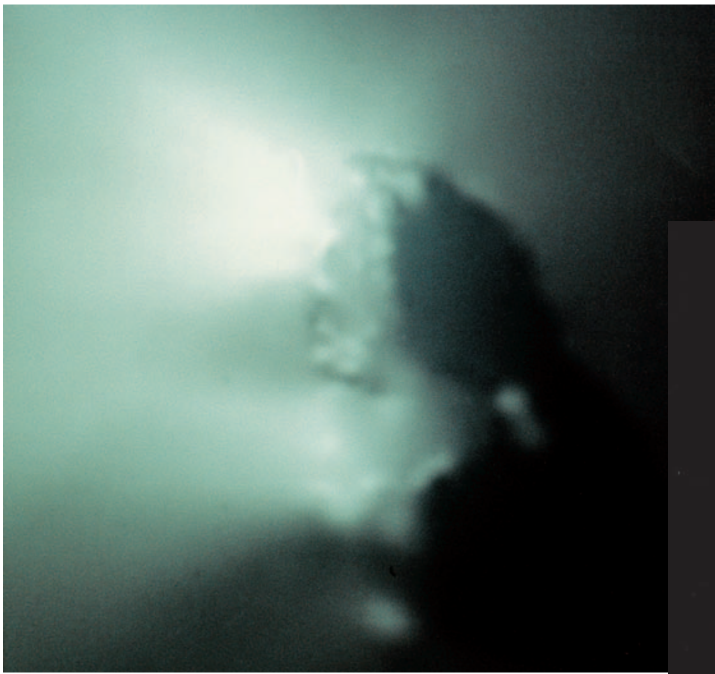
The IHW later became the role model for all future campaigns mounted to provide support for flight projects to comets. The Rosetta mission has been building up a network of ground-based observatories to monitor its target comet since the mission was first approved ten years ago, and our US colleagues have been following this example for the Deep Space 1 and Stardust missions. On 4 July 2005, ground-based telescopes around the World, the NASA/ESA Hubble Space Telescope, and ESA's Rosetta mission all monitored the impact on comet Tempel 1 of NASA's Deep Impact spacecraft.

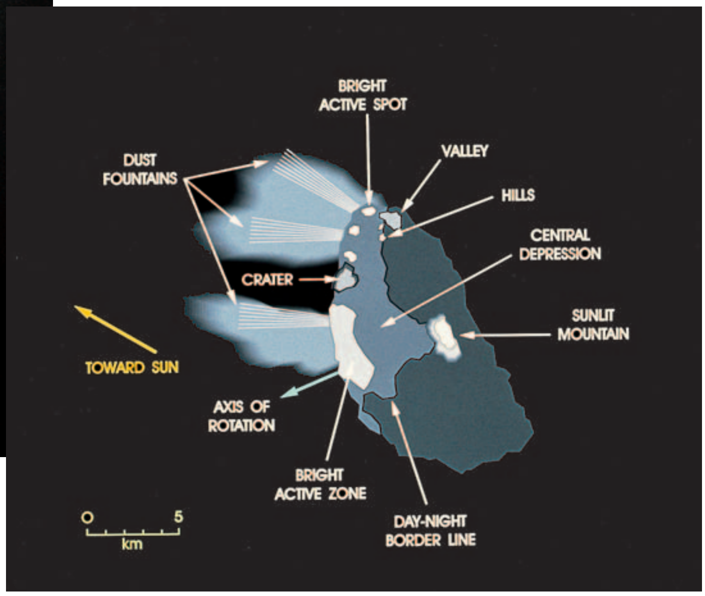
The Halley Results in a Nutshell

The first results from the encounters with Halley were published in a joint publication in *Nature*, coordinated by the IACG. The most striking results were the images from the Halley Multicolour Camera on Giotto, which revealed that the comet had a single nucleus with an elongated, potato-like shape, being about 15 km long and 9 km across, and was thereby larger than previously anticipated. The fact that we could determine the body's albedo directly for the first time led to the discovery that only 2-4% of the



Far-ultraviolet image of comet Halley taken from a sounding rocket at an altitude of 194 miles on 13 March 1986, just 13 hours before Giotto's closest approach to the comet. It highlights in false colours the hydrogen cloud surrounding the nucleus. (Courtesy of NRL, Washington DC)





Left: Composite of seven Halley imges, highlighting details on the nucleus and the dust jets emanating from the sunlit side (Courtesy of H.U. Keller, MPS)
Right: Principal features identified in Giotto's images of comet Halley

incident light was reflected, which means that comets are among the darkest objects in the Solar System. Two major bright jets emanated from the sunward side of the nucleus and it appeared – and this was one of the big surprises – that only a relatively small fraction of the nucleus was active. Combined with other observations, it was possible to establish that the nucleus had a fairly low density, at < 0.6 g/cm^3.

Giotto's Neutral and Ion Mass Spectrometer provided a wealth of data on the composition of the comet's molecular structure, including detailed information about the abundances of the various species as a function of distance from the nucleus. From the analysis of the dust spectra, we learned that most of the dust particles were rich in hydrogen, carbon, nitrogen and oxygen, with minerals and most probably organic components present, which is characteristic overall of a very complex chemistry.

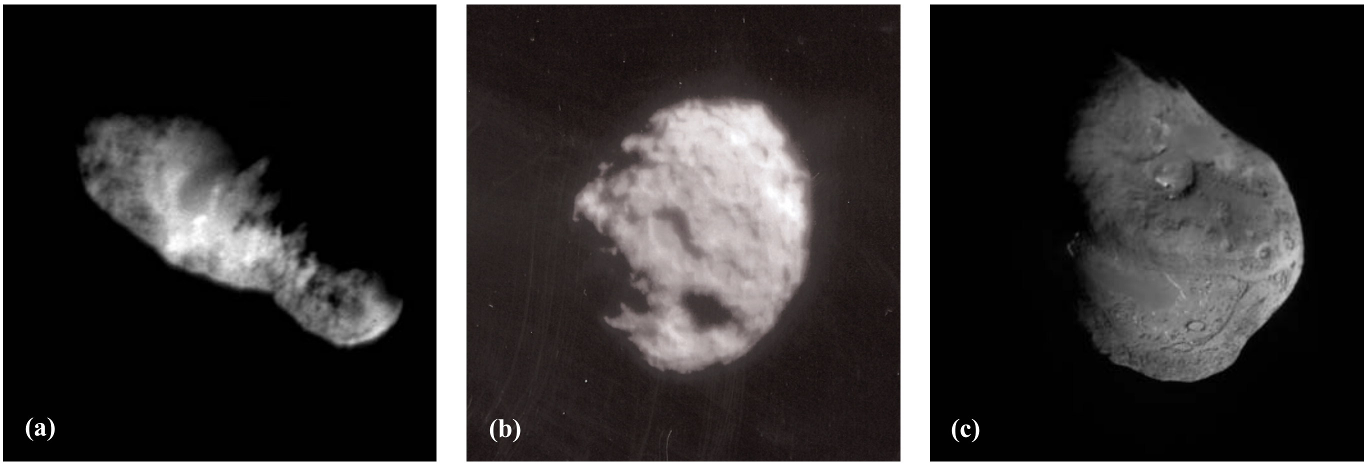
The first dust-particle impact on the Giotto spacecraft was recorded by the Dust Impact Dectection System when still 290 000 km from the comet's nucleus, which was much further away than predicted by the dust models. More than 12 000 dust-particle impacts were recorded during the fly-by, with particle masses ranging from 10^{-17} to 4 x 10^{-2} g. From these measurements, a dust production rate of approximately 3 x 10^6 g/s was derived.

The interaction between the solar wind and the comet's ionosphere can be characterised by two distinct boundaries, the bow shock and the contact surface, and several additional sharp transition regions, which indicate a multi-layered interaction region. The Giotto data are textbook examples for these interaction regions. The spacecraft crossed the bow-shock region when 1.15 million km from the nucleus, and crossed the contact surface when 4700 km away. Inside this region, the magnetic field dropped essentially to zero, as had been theoretically predicted and had been expected by analogy with Venus and the 'artificial' comet of the AMPTE mission.

The Post-Halley Era

Giotto's visit to comet Halley certainly taught us a great deal, but as always with such exploratory missions it also raised new questions, whetting the scientific community's appetite for learning even more about these fascinating primordial space objects and prompting calls for more cometary missions. A few weeks before the launch of Giotto, a number of planetary scientists had met in Zurich (CH) to prepare an input for the Agency's long-term scientific programme known as 'Horizon 2000', which contained a so-called 'Planetary Cornerstone' mission. They already wanted it to become a Comet-Nucleus Sample Return (CNSR) mission in collaboration with NASA, which would represent a logical next step after Giotto. In the mid-nineties, when it turned out that NASA would no longer participate, it became an ESA-led mission and was redefined as a cometary orbiter with a lander. This Rosetta mission was launched on 2 March 2004 and is currently on its way to comet 67P/Churyumov-Gerasimenko, which it will reach in mid-2014. *"When we can't bring back a sample to the laboratory, we have to bring the laboratory to the comet"* was the motto under which Rosetta's state-of-the-art payload has been developed.

The US colleagues who had originally



The different faces of comets: (a) Comet Borelly (resolution ± 60 metres); (b) Comet Wild 2 (composite image, resolution ±20 metres); (c) Comet Tempel 1 (composite image, scaled to 5 metre resolution) (Images courtesy of NASA)

criticised flyby missions to comets even in the exploratory phase as not providing a good scientific return were eventually won over by the tremendous success of Giotto and the wealth of data that it and the Vega1 and 2 spacecraft provided. Consequently, NASA's Deep Space 1 mission, launched on 24 October 1998 with the prime objective of the in-flight testing of new technologies, and solar electric propulsion in particular, went on during its extended mission to fly-by comet Borelly in September 2001.

Three cometary missions then followed as part of NASA's Discovery programme. Stardust, launched on 7 February 1999, passed comet Wild 2 on 2 January 2004 at 240 km and collected comet grains that were returned to Earth on 15 January 2006. It was followed by Contour, a mission to study the diversity of comets by making close fly-bys of at least two of them, in a similar manner to Giotto. Launched on 3 July 2002, that spacecraft was unfortunately lost during the main-engine burn that should have injected it into its interplanetary trajectory. The third spacecraft Deep Impact, launched on 12 January 2005, fired a projectile into comet Tempel 1 on 4 July 2005, an event that was monitored by observatories around the World.

Giotto was therefore instrumental in improving our fundamental knowledge about comets. Based on its results and the follow-on missions that it spawned, we have gradually learned more and more about these mysterious bodies over the past decades. Our ground-based observing techniques have also improved tremendously, and we have now a couple of very large telescopes at our disposal, something that we could have only dreamed of in 1986. But when we compare the images of the various comets, we realise that they all look quite different. Why, we don't really understand yet! A lot of questions have been answered, but the more we have discovered, the more we want to know in order to really understand comets, their origin, their physics and their chemistry. ESA's Rosetta will be the next spacecraft to visit a comet, in 2014, this time to make detailed, longer-term studies. Based on what we have learned so far from these 'frozen snowballs of mud and ice' that periodically crisscross the firmament, it will certainly be worth the wait!