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The constituents of cometary nuclei

Close to the edge of our Solar System is a cloud containing many tiny objects only a few kilometers in diameter. Even though their number has been estimated to be as large as $\sim 10^{13}$, their total mass is still negligible compared to that of the major planets. Their existence would go unnoticed were it not that, from time to time, some of them are gravitational by pertured and move inward, towards the Sun, and can then be observed as comets. Several space missions have been aimed uniquely at comets, among them the first European deep space mission, Giotto. Rosetta, a cornerstone mission of the Horizon 2000 program of the European Space Agency (ESA), is one of several comet missions being planned for the first decade of the twenty-first century. Why do comets deserve this special attention?

Comets streak brilliantly across the night sky, their tiny nucleus obscured behind an immense coma. Their long tails set them apart from all other celestial bodies, and their sometimes sudden, unexpected appearance and unusual paths across the night sky have stimulated the imaginations of skywatchers for thousands of years. In ancient China details of comets were meticulously recorded – their time of appearance, location and shape. For a long time the origin of comets was believed to be divine. Comets were usually associated with major happenings in the history of nations: lost battles, the death of a king, natural disasters. In the seventeenth century the English astronomer Edmund Halley proved that comets are not doomsayers dispatched by a supernatural being, or atmospheric phenomena, but bodies in our Solar System following their own trajectories.

The myth of the special significance of comet apparitions, however, has survived into modern times: when the large and brilliant comet Hale–Bopp appeared in 1998, there were some who saw the apparition of this comet as a divine sign, and hid in shelters or even committed mass-suicide.

But although comets were reduced from divine objects to members of the Solar System by the work of Edmund Halley, they have retained their special significance for scientists. It has been recognized that, while comets cannot tell us about our future, they can at least provide a wealth of information about the history of our Solar System. Comets provide insights into the origin of planets and the fate of the dark molecular cloud, long since disappeared, from which the Solar System – including our Earth – emerged.

COMETARY CONSTITUENTS AND THE ORIGIN OF THE SOLAR SYSTEM

The origin of solid matter can be divided into three phases: the synthesis of the atomic nuclei, the formation of molecules from atoms, and the condensation of gaseous atomic and molecular matter into solids. The history of cometary matter is complex, and is shown schematically in Figure 1. Atomic nuclei are synthesized in the interiors of stars and released into the interstellar medium at particular stages of stellar evolution (red giants, supernovae and novae). Condensation into solid grains occurs when densities are high and temperatures fall, as happens in stellar envelopes or remnants of stellar explosions (producing high-temperature condensates), molecular clouds (producing low-temperature condensates) and protostellar disks.

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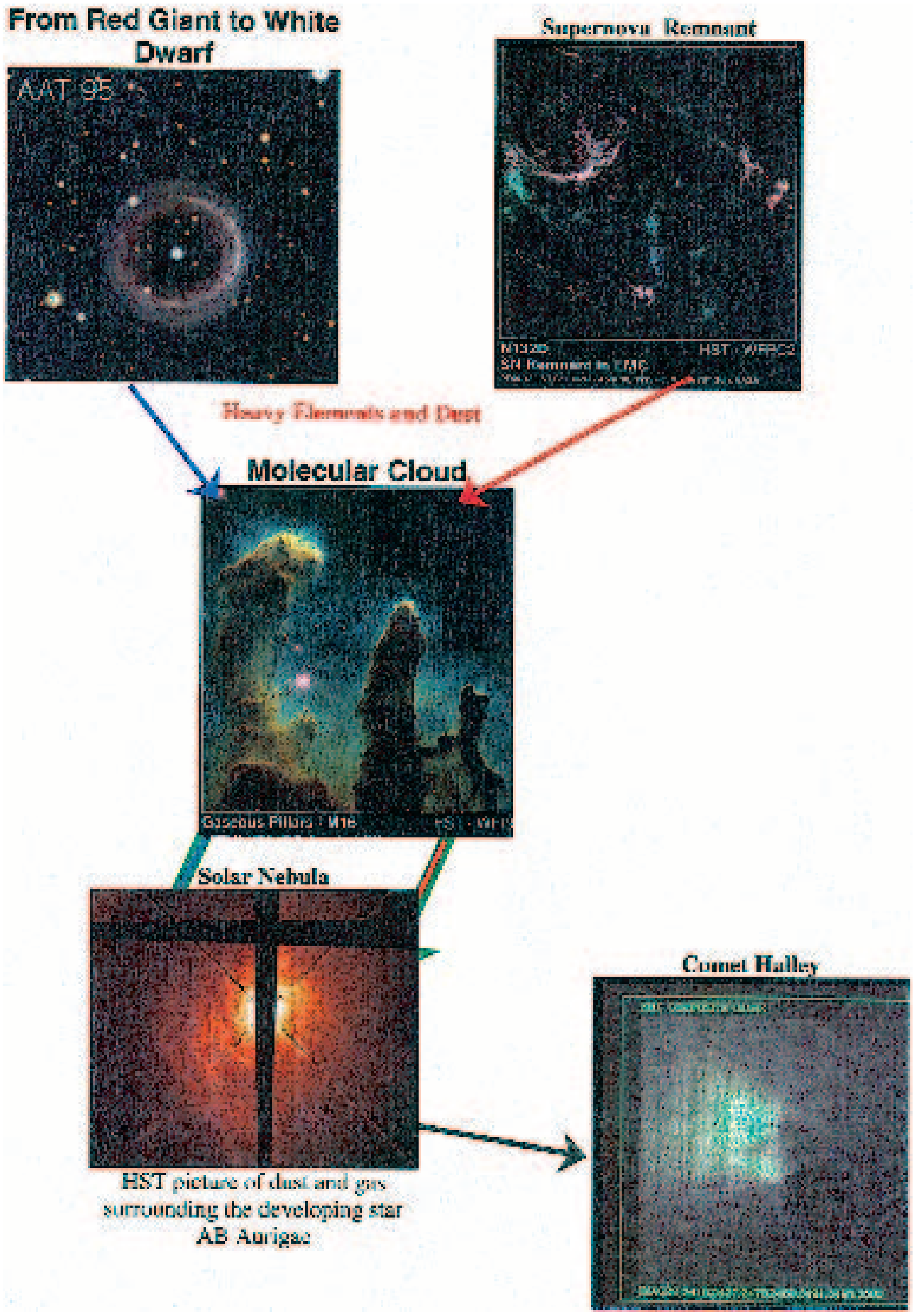

Figure 1 The origin of molecules, ice and dust in comets (after Geiss and Altwegg 1998).

Different stellar sources release matter with very different isotopic signatures, which are preserved in grains. The stellar origin of grains can therefore be identified from isotope abundance determinations, a method that has been applied with great success to certain refractory grains isolated from meteorites (e.g. Hoppe *et al*. 1996). Comets are expected to have preserved a larger variety of grains with the original stellar signature than meteorites. So far, however, such isotopic evidence is scarce. A few grains with high and variable $^{13}C/^{12}C$ ratios were found in the coma of

Comet 1P/Halley (Jessberger and Kissel 1989) indicating multiple stellar origins. More such results should be obtained by the Stardust and Rosetta missions.

Grains of stellar origin are mixed into the interstellar medium. When molecular clouds are formed, the grains may serve as nuclei for the condensation of more volatile molecules. Upon the dispersion of such clouds into the diffuse interstellar medium, the mantles of the grains can be processed by ultraviolet and particle radiation (Greenberg 1989). Material can be cycled many times between molecular clouds and the diffuse interstellar medium. About 4.6 Gy ago a galactic local protostellar molecular cloud partially collapsed to form several protostellar disks, among them our own protosolar cloud. During the collapse phase, and in the solar nebula, many grains and their volatile content were evaporated and recondensed prior to the accretion of the solid bodies of the Solar System.

Fred Whipple (1950) was the first to recognize the importance of comets for the history of the Solar System. In the last decades of the twentieth century it became accepted that comets contain the most pristine material to be found in any of the bodies in the Solar System. They were created far from the early Sun, and spent almost their entire lifetime at the edge of the Solar System, where the influence of the Sun was minimal, so they provide a reservoir of well-preserved and minimally altered material from the solar nebula. In studying this material we can deduce physical and chemical boundary conditions for the accretion of cometary material in the solar nebula. We can trace the origin of some cometary molecules to the dark molecular cloud from which the solar nebula emerged, and thus study the processes that led from the molecular cloud, through accretion into the solar nebula, to the present constituents of cometary nuclei.

COMETARY SPACE MISSIONS

The Halley fleet

In the 1970s scientists began to prepare for the 1985/6 apparition of Comet 1P/Halley. Halley is the most famous of all comets, and there were many who still remembered its last magnificent apparition in 1910. Since the 1960s, space missions had explored many of the planets and the technology for mounting a mission to a comet was available. It was therefore obvious that Halley would present a scientifically worthwhile and a technically challenging goal for a space mission, which at the same time would stimulate the interest of the public. ESA and NASA planned a joint mission in which a NASA-built spacecraft would head for a rendezvous with Comet Tempel 2, releasing en route an ESA-built probe that would be directed to encounter Halley. However, when NASA failed to obtain support for this mission from the US Government, ESA proceeded alone, and the mission was redefined from a rendezvous to a flyby mission to be launched on the European rocket Ariane 1. The time between the approval of this mission and the launch date was only five years. It was the first European planetary mission, and it took a great effort from both ESA and the different experiment teams to build the spacecraft and its payload on time. The spacecraft was named after the Italian painter Giotto di Bondone, whose frescoes of the adoration of the Magi painted in 1301 at the Scrovegni Chapel, Padua, used Comet Halley as the Star of Bethlehem (the comet was visible in the night sky at that time).

The Giotto spacecraft, with a sophisticated payload of ten instruments, was launched in June 1985 from Kourou in French Guiana. Giotto was not the only spacecraft to make the journey to Halley. A whole fleet, completed by two Japanese and two Russian spacecraft, was launched – other nations had recognized the scientific and public interest of comets. In addition, NASA reprogrammed its International Cometary Explorer (ICE) spacecraft (formerly ISEE 3, the third of the International Sun–Earth Explorer series) towards the tail of a comet. ICE went through the tail of Comet 21P/Giacobini–Zinner in 1985, becoming the first spacecraft ever to probe a comet *in situ*, and detect ions from the water group (Ogilvie 1985). It was then redirected towards Halley, passing upstream around 0.2 AU from Halley on 27 March 1986, and gathering data on the interaction of the comet with the solar wind.

The exploration of Halley's Comet led to an unprecedented intensive international cooperation. The International Halley Watch, co-ordinating the activities of astronomers and telescopes from all over the world, was initiated. Furthermore, a 'pathfinder' concept was established between Russia and ESA. The two Russian spacecraft, Vega 1 and Vega 2, flew past the comet at distances of 9000 and 8000 km, respectively, a few days before Giotto. They transmitted to ESA the exact position of Halley's nucleus, allowing Giotto to execute the very precise manoeuvre that would enable it to pass the comet's nucleus at the predefined distance of 600 km.

During the night of March 13/14 1986, people interested in cometary science either sat in the control centre in Darmstadt intently watching the computer screens as the Giotto data were received, or followed the events on television. But only the succeeding months and years revealed the wealth of data acquired during the few hours of the flyby.

Giotto survived this encounter, although its subsystems and the payload were damaged by dust impact. It was decided to redirect Giotto towards a second comet, 26P/Grigg–Skjellerup. Giotto became the first European spacecraft to enter a long hibernation phase and to make use of a planetary gravitational assist. In 1990, after four years of hibernation, it passed the Earth at a distance of ~23,000 km, and finally in July 1992 it passed comet Grigg–Skjellerup at a distance of 95 km. Another 'night of the comet' was celebrated in Darmstadt and on television. Grigg–Skjellerup is a short-period comet, but not very active. The flyby geometry was very different from that at Comet Halley, and the scientific results were somewhat less, but the data collected led to some interesting and novel findings about the interaction between comets and the solar wind. Analysis of the Giotto data from the Halley and Grigg–Skjellerup encounters continued throughout the 1990s.

Giotto's flyby of Comet Halley was certainly one of the highlights of ESA's space program in the twentieth century. But the Russian spacecraft also proved very successful. For Japan, the two spacecraft Suisei and Sakigake were the first successful planetary missions. The absence of NASA's participation in the Halley space armada was notable, and leadership in the space exploration of comets passed to ESA through the Giotto spacecraft and its particularly close flyby of Comet Halley.

Future space missions

In the 1990s the importance of cometary science was definitely established. The two great comets of that decade – Hyakutake (C/1996 B2) in 1996 and Hale–Bopp (C/1995 O1) in 1997 – triggered further interest in comets. This led to a big step forward in remote sensing of cometary constituents. But it also became evident that *in situ* measurements were far superior for a full picture of the nature of comets. New comet missions were planned in the 1990s which have not yet been launched or have not yet reached their goal. The US Comet Rendezvous and Asteroid Flyby (CRAF) mission, planned just after Giotto, was cancelled in 1991. The European Rosetta mission, originally planned as a sample-and-return mission jointly with NASA, was redefined to an ESA-built comet rendezvous mission with a German-built lander. It will be launched in January 2003 for a 2011 rendezvous with Comet 46P/Wirtanen, which will then be near aphelion. The spacecraft will accompany the comet in close vicinity through its perihelion passage in 2013. NASA launched the Stardust mission in 1998; a small mission aimed at collecting dust in the coma of Comet 81P/Wild 2. Stardust will return its sample to Earth in January 2006. In addition, NASA is redirecting its Deep Space 1 spacecraft to flyby the comets 19P/Borrelly and 107P/Wilson–Harrington. NASA is planning two additional missions, the CONTOUR mission to flyby three comets – 2P/Encke in 2003, 73P/Schwassmann–Wachmann 3 in 2006 and 6P/d'Arrest in 2008 – and Deep Impact, which will direct an impactor at comet 9P/Tempel 1 and examine the results during a flyby mission in 2005.

KNOWLEDGE OF COMETARY CONSTITUENTS BEFORE THE HALLEY ENCOUNTER

Before 1900

The first measurements of comet composition were made by astronomical spectroscopy in the first half of the twentieth century, but speculation on the composition of comets has a longer history. Ancient popular traditions held that comets are responsible for major effects, generally negative, on earthly life during their apparitions. Isaac Newton – whose *Principia* created a major scientific breakthrough in understanding the motion of heavenly bodies, including comets – was himself influenced by these beliefs, and was convinced that emanations from comets could lead to the spontaneous generation of plant life (Oparin 1938). Newton's more certain connection with comets was through his relationship with Edmund Halley, who prompted Newton to write *Principia* and also funded its publication.

Speculation related to the composition of comets also appeared during the nineteenth-century debate over Darwin's theory of the evolution of life. Unlike the rival theory of spontaneous generation, Darwin's concepts of natural selection and common ancestry required a singular and ancient origin for all life. The concept of panspermia was brought to bear on this issue by von Helmholtz (1871), who wrote, 'Who can say whether the comets and meteors which swarm everywhere through space, may not scatter germs wherever a new world has reached the stage in which it is a suitable place for organic beings.'

1900–1950

At the opening of the twentieth century the idea of panspermia, that the Earth was seeded with life from space, particularly by comets, was one of the leading explanations for the origin of life on Earth and had many proponents, including Lord Kelvin and Svante Arrhenius. Thomas Chamberlin (1911) attacked the idea that spores could be driven across the Universe to transport life from planet to planet, and proposed an alternate hypothesis that 'planetesimals', the small bodies out of which the planets formed, could have been a source of organic molecules on the early Earth.

According to Chamberlin and Chamberlin (1908), organic molecules imported to the early Earth by infalling planetesimals could have been the basis for abiotic chemical evolution on the young planet that would produce the chemicals necessary for life. Chamberlin was clearly influenced by the nineteenth-century discoveries of organic compounds in meteorites (Berzelius 1834, Wöhler 1858, Wöhler and Hoernes 1859). Chamberlin's work was aimed more towards an understanding of the origin of the Solar System, but included the original insight linking the origin of Earth with that of life on the planet. This work went essentially unnoticed until the end of this century (Oró and Lazcano 1996).

By the end of the first quarter of the twentieth century, the first detection had been made of molecular species in comets. The new technique of astronomical spectroscopy in

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