

Comets: A Key to Solar System Formation

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Dedicated to Professor H. Wänke on the occasion of his 60th birthday

Four lines of information on comets are discussed: their orbits, their relation to other bodies of the planetary system, their physical state and chemical composition, and implications of recent observations of the nucleus of comet Halley. The in situ measurements during the flybys of comet Halley strongly support the assumption that comets are members of the solar system and were created during its formation. The region (heliocentric distance) of their formation is, however, still difficult to assess. The size, shape, and topography of the cometary nucleus suggest that it was formed from relatively large subnuclei in a region of the primordial solar nebula where relative velocities were sufficiently small. There are indications that some of the interplanetary dust particles in the Earth atmosphere may originate from comets.

Key words: Comets, origin of comets, cometary nucleus, comet Halley, cometary composition, cometary dust.

Introduction

The role of comets in our understanding of the formation and development of our solar system has become more prominent over the past 20 years. Comets differ greatly from other bodies of the solar system. The question whether they have been members of the planetary system from its formation about 4.5 Gy ago has repeatedly been debated. New comets that come into the inner solar system on almost parabolic orbits are very loosely bound by the gravitational field of the Sun. Capture scenarios are conceivable. Another possibility is the ongoing formation of comets from interstellar 'debris' by the interaction of the solar system with its surroundings. Consideration of the orbital properties alone is not sufficient to resolve the question of the origin of comets. Additional information from direct observations of comets is required.

Deductions of the chemical and physical properties of comets have become more sophisticated. Spectra in the visible wavelength range show resonance lines of simple, mostly diatomic radicals that are obviously dissociation products of more complex 'parent molecules'. Products of further dissociation, the atoms, have become accessible for investigation only in the past 15 years during the era of UV observations [1].

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This yielded information on the mean atomic composition (H, O, C, S; N has not been detected) [2] of the volatile cometary material. Indirect evidence (e.g., H to OH ratio and its variation with heliocentric distance) [3] has supported common belief that water is the dominant molecule of the volatile component in comets. More recently, improved sensitivity of IR-spectroscopy made it possible to observe the most dominant parent molecules directly [4]. It is generally thought that the cometary material is pristine, i.e. cometary material has not been processed during and after the formation of cometary bodies. Cometary nuclei are too small for accretional heating. Only radioactive decay of ^{26}Al could have provided enough heat for a significant temperature increase in the cometary nucleus [5], [6]. The possible pristine nature of comets sets them apart from all other bodies of the solar system. The inner part of the planetary nebula was heated (possibly by solar flares) to many hundred degrees leading to a loss of volatile elements [7]. All bodies in the inner solar system are therefore fractionated relative to the average solar system composition [8]. Some moons of the outer planets show an icy surface but their large size implies that they were compressed and heated by self-gravitation [9].

The suspected absence of thermal metamorphism in comets makes them outstanding candidates for the investigation of the physical and chemical conditions of the original material at the location of accretion of

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cometary matter; certainly outside the hot inner region and probably near or beyond the outer planets.

There are 4 major fields of study from which we may gain knowledge on the nature and origin of comets: their orbits, their relation to other bodies of the solar system, their chemical composition, and only recently, the physical properties of the cometary nuclei. The intention of this contribution is to summarize briefly our present knowledge and to highlight explicitly the most recent results from the optical observations of the nucleus of comet Halley and discuss the implications for our understanding of the nature and origin of comets, and, hence, the solar system.

The Orbits of Comets

When Sir Edmund Halley's prediction of the return of the comet seen in 1682 (and earlier in 1607 and 1531) was fulfilled it became evident that (periodic) comets are members of the solar system. Comet Halley is exceptional being the brightest of the short period comets. All other short period comets (and here short means compared to the time of observation by man) either cannot at all or can just barely be observed by the naked eye. They are too dark and too inactive. The exciting appearances of comets sometimes covering the night sky from horizon to horizon are all long period comet with almost parabolic orbits. The statistical distribution of the orbits of these comets led Oort (1950) [10] to the postulate of a cloud of 10^{12} comets surrounding the Sun. This cloud extends almost to the spheres of influence of the neighbouring stars. Passing stars perturb the cometary cloud (with an average frequency of 1 per 20 My) resulting in a few comets that directly approach the Sun while passing through the inner solar system. A random change of the direction of motion at 10^5 AU from the Sun yields a chance of only $(10^5)^{-2}/4\pi$ for a comet to cross the Earth's orbit. A large number of comets is therefore required to account for the small number of comets observed from Earth. Also some comets with parabolic orbits will interact with the gravity field of Jupiter. Comets with orbits near the ecliptic plane will preferentially be gravitationally perturbed and may end up (after several encounters) as short period comets. While this scenario is attractive for an explanation of cometary apparitions and the distribution of orbital parameters of comets at global view, numerical calculations of the orbital evolution (e.g. [11]) do not produce a satisfactory yield of

comets. As a result, an "inner" Oort cloud was postulated [12] reaching from just beyond the outer planets to about 10^4 AU. The transition of comets from this region into observable short and longer period comets seems somewhat more effective since the orbits of these comets in the inner cloud would be concentrated toward the ecliptic plane. In some scenarios short and long period comets are members of two different populations [13], [14]. Whether these populations are distinct with respect to their formation and composition is an open question.

The mass, structure, and the dynamical evolution of the present Oort cloud are consequences of its formation process(es). Similar to the cometary capture process, a quantitative problem also exists for the *formation* of the Oort cloud. If comets were formed as bodies of the primordial planetary system their orbits would also have been concentrated near the ecliptic plane. What are the detailed processes that formed the large number of comets (most of them presumably lost to interstellar space), transported them to the extended Oort cloud, and randomized their orbital planes? These remain exiting and challenging questions.

The stability of the Oort cloud over the age of the solar system (4.5 Gy) has been questioned [15]. The solar system should have encountered 20 to 30 giant molecular clouds during its lifetime. The perturbations of any such an encounter would be disastrous for the comets in the outer Oort cloud as they would be stripped away. An inner cloud ($<10^4$ AU) would also be strongly perturbed leading to ejection of comets into the inner planetary system and to cometary orbits extending out to the reaches of the classical Oort cloud and beyond.

Our understanding of the dynamical evolution of the comets is closely connected with the location of their origin. Several possibilities exist: (a) in the outer planetary system (Neptune region) [12], (b) at the fringes of the protoplanetary dust disk ($r < 10^4$ AU) [16], or (c) satellite systems, i.e., presolar nebulae too small to form a sun (e.g. [17]). The difficulties of the formation and evolution of the cometary cloud and the recapture of comets into the inner solar system have led to investigations of alternate concepts. Continuous formation of comets from interstellar material or repetitive (episodic) capture of interstellar comets have been proposed. A recent discussion of these possibilities was given by [18]. The problems and uncertainties are widely considered to be more severe than for those of the original concept developed by Oort.

Comets and Their Relation to Other Solar System Bodies

Asteroids

The question of the fate of “burnt out” comets has become more interesting after recent results from the spacecraft flybys of comet Halley. It seems very likely that cometary nuclei do not sublime completely but rather become extinct as bodies in the size range of 10 km. They are similar in appearance to asteroids [19], however, do not readily match the taxonomy of any asteroid class, at least not in the case of comet Halley [20]. Are some asteroids extinct cometary nuclei? For some time the Earth crossing groups of the Apollo-Amor families have been connected to extinct comets [21]. Their elliptical orbits (similar to those of short period comets) differ from the almost circular orbits of most other asteroids. The recent quantitative assessment of collisions in the asteroidal belt and of the Jovian influence (via resonances) [22] on the dynamical evolution of the orbital motion still leaves open the possibility for a major contribution of extinct cometary nuclei to Earth-crossing objects [21].

Asteroidal material is accessible in laboratories in the form of meteorites [23]. While the abundances of the rock-forming refractory elements in cometary dust particles are similar to those found in the most primitive CI carbonaceous chondrites, cometary material shows an excess of light elements that compares to solar values (with the exception of H). A further discussion is given below.

Interplanetary Dust

A cloud of dust particles orbits the Sun within the inner solar system. Inside the asteroidal belt this cloud (the zodiacal cloud) has a mass of 10^{19} to 10^{20} g [24] and seems to be a mixture [25] of dust particles originating from asteroids and comets. The cloud is dynamically unstable, loosing particles that spiral into the Sun driven by the Poynting-Robertson effect. Assuming steady state, about 10 Mg s^{-1} need to be replenished [24]. Estimates show that short period comets may suffice as a source for the zodiacal cloud. In situ measurements of the dust particles [25] indicate a 2 to 1 ratio of particles from asteroids compared to comets, differentiated by the eccentricities and inclinations of the particle orbits and their densities. Further outside the asteroidal belt ($> 3 \text{ AU}$) particles seem to

have a very low albedo and probably originate exclusively from comets [26, 27].

Dust particles in the inner solar system are heated by solar electromagnetic radiation and are bombarded by solar wind particles. This could lead to loss of volatile components and even to changes in their physical structure [28]. The Earth intercepts these interplanetary dust particles (IDP) and they can be collected in the upper atmosphere using high flying airplanes [29]. Some of these “Brownlee” particles have low density (around 1 Mg m^{-3}). Their chemical composition is rather similar [30] to the silicate component of dust particles analyzed in the vicinity of comet Halley [31–33]. In particular the $\text{Fe}/(\text{Fe} + \text{Mg})$ distribution of anhydrous IDPs shows a strong maximum at low values rather than the typical value of 0.5 for layer lattice silicate material. The distribution found from the analysis of the comet Halley dust grains also concentrates at low values with a secondary maximum at the central value. This could indicate an admixture of layer lattice silicate grains to the predominantly anhydrous bulk material [34]. The $\text{Fe}/(\text{Fe} + \text{Mg})$ distribution of the Halley dust grains (and the anhydrous IDPs) is very rare in meteoritic matrix material and therefore sets the cometary material apart from bulk meteoritic compositions [35].

Further comparison of the spacecraft results and the analysis of stratospheric particles could provide evidence for the cometary origin of some of these particles. In this case we would be in a similar position as Mars researchers proposing a martian origin for SNC meteorites. Cometary material (possibly altered) would be available in the laboratory for detailed analysis.

The Composition of Comets

Research into the chemical composition of the volatile gaseous components of comet Halley yielded few surprises. The progress in the techniques of spectroscopy (see e.g. [36]) and the extension of the accessible wavelength ranges made the conclusions on the parent molecules of the visible radicals quite reliable. The icy subliming component of the nucleus of comet Halley is predominantly composed of water H_2O (80%), CO (5 to 15%) and CO_2 (3.5%). All other compounds range in the order of 1% (see Table 1, [37]). The CO density distribution near the nucleus does not follow the r^{-2} law of material expanding from the nucleus (a

Table 1. Abundances of probable parent molecules in the coma of comet Halley. With few exceptions the data were obtained on March 6 and on March 14, 1986, at heliocentric distances of 0.79 and 0.89 AU, respectively. For more details see [37].

Species	Gas Production Rate Relative to H ₂ O	Instrumental Technique
CO	0.05 ... 0.07 0.17 ... 0.20 0.13 ... 0.15	Giotto NMS, gas spectra Rocket UV experiment Giotto NMS, gas spectra
CO ₂	≤ 0.035 0.015	Giotto NMS, gas spectra Vega 1 IKS, IR spectra
CH ₄	≤ 0.07 ≤ 0.04 ≈ 0.02	Giotto NMS, gas spectra KAO, IR spectra Giotto IMS, ion spectra
NH ₃	≤ 0.1 0.01 ... 0.02	Giotto NMS, gas spectra Giotto IMS, ion spectra
N ₂	≤ 0.02 < 0.02	Giotto NMS, gas spectra Giotto IMS, ion spectra
saturated hydrocarbons	≈ 0.01	Vega 1 IKS, IR spectra
unsaturated hydrocarbons	≈ 0.01	Vega 1 IKS, IR spectra
H ₂ CO	≈ 0.01	Vega 1 IKS, IR spectra
HCN	≈ 0.001	IRAM telescope, millimetre spectra

point source). The distribution is shallower [38] indicating a distributed source. Only a fraction of the CO (about 1/3) comes from the nucleus. Dust particles coated by semi-volatile material, that evaporates when the particles are heated up by the Sun and dissociate to produce CO, are suspected as the coma source [39]. This result must be compared to the detection of weak jet like structures in the emissions of CN and also C₂ [40, 20, 41]. The coating of dust particles with semi-volatile, organic material was detected by the dust mass spectrometers flown on the Vega and Giotto spacecraft [31, 32] (see below).

Isotope ratios of hydrogen, oxygen, and sulphur have been determined from the spacecraft flyby data [42]. All lie within the range expected for solar system materials. The D/H ratio (between $0.6\text{--}4.8 \times 10^{-4}$) is similar to values found at Uranus and Titan as well as for the Earth's atmosphere. Does this indicate a relationship between these bodies connected via comets? This is open to debate.

Considerable excitement was created by the results of the dust observations. The dust counting experiments [43–45] showed a strong excess of small particles compared to the distribution derived earlier from ground-based observations [46]. In fact there seems to

be a continuous size distribution, from large particles with dimensions of centimetres that comprise the bulk of the mass to molecular clusters with dimensions in the range of 10 to 100 nm [47]. The density of many small particles was less than one, indicating a large porosity [48]. The mass spectra revealed large compositional variations from particle to particle. Surprisingly, some particles showed spectra consisting of C, H, O, and N (CHON) only, while others seemed to be similar to the expected chondritic material (silicate component) [49, 50]. Most particles were mixtures of these two components. The dust of comet Halley is on average less "metamorphosed" [34] than the most primitive meteoritic material and therefore reflects to a greater extent the original composition of the solar system. As discussed above, the organic component of the dust particles contributes to the gas component of the cometary coma. Again we see a continuous range, this time in volatility; from volatile ices (the classical gas component H₂O or more volatile compounds) to refractory particles (the classical silicate dust grains). The notion of a cometary 'dust grain' has changed. Not only do they comprise the meteoritic (silicate) material but also the semi-volatile (organic) material that sublimates at temperatures considerably higher than the equilibrium temperature of water ice (200 K).

The composition of the dust grains and the gas reveals that comets contain a large fraction of volatile material, larger than any other small body in the solar system. The volatile elements are enhanced compared to CI carbonaceous chondrites while the non-volatile compounds display a similar composition [51]. Unfortunately, the dust-to-gas mass ratio is poorly known since most of the dust mass is contained in the large particles that cannot be observed in the visible. The statistics of impacts during the flybys were poor and the dust distribution was inhomogeneous. While earlier estimates of the dust-to-gas ratio centered around 0.5 or were even smaller [46], values up to 10 are now considered (see [52] for a critical review). Solar abundances for cometary material (in particular for the C/Mg ratio) would lead to a dust/gas ratio of one [53].

Cometary material seems to consist of a very porous non-volatile matrix. The smallest units (cores) may be coated with semi-volatile (organic) complex compounds and more volatile molecules, predominantly water ice. These particles may originate from interstellar material that formed the molecular cloud of the collapsing presolar nebula [54].

The formation of the planets from the coalescing particles in the presolar nebula takes only 10^5 to a few 10^6 years [55], presumably not enough time to form complex organic substances from simpler components by reactions on the surfaces of dust grains [56, 57]. These complex molecules were probably created in the dense molecular cloud before the collapse. The coating by the volatile water component could then have taken place during the formation of the cometesimals. The presence of volatiles such as CO requires that the temperature of the coalescing grains did not reach temperatures in excess of 50 K. Quantitative statements are difficult since important processes in the formation of the early planetary system were not in equilibrium [7, 58].

The Nucleus of Comet Halley

For the first time it was possible to observe the physical properties of a cometary nucleus during the flybys of the Vega 1 and 2 and the Giotto spacecraft in March 1986. In particular the Halley Multicolour Camera (HMC) on board the Giotto spacecraft [59], operating as close as 1600 km from the nucleus, revealed details on its surface. The global shape of the nucleus could be derived from the observations by the Vega spacecraft [60] taking images at a minimum distance of 8000 km from 3 sides. The overall properties of comet Halley’s nucleus are listed in Table 2. The nucleus was considerably larger than the anticipated radius of 3 km [46]. Its albedo was very low, less than 4%; it is one of the darkest objects seen in the solar system. During the Giotto encounter most of the nucleus was in the dark, not illuminated by the Sun that was about 17° behind the image plane during approach of the spacecraft. Figure 1 displays a sample of HMC images taken from distances between 124,000 and 2000 km. Figure 2 is a combination of images in order to display the high resolution parts within the frame of the whole nucleus.

The cometary nucleus is large and rather irregular when compared to a sphere. It can be approximated by a symmetric ellipsoid of $(16 \times 7.4 \times 7.4) \text{ km}^3$, being an elongated body. The present shape could hardly evolve from a sphere by sublimation. It could be a fragment of a much larger body or, more probably, it is a conglomerate of subnuclei of various size. The depression at the centre of the nucleus could be interpreted as a waist separating two large subnuclei. In

Table 2. Physical parameters of the nucleus of comet Halley derived from the observations of the Halley Multicolour Camera and Vega 1 and 2.

Comet Halley’s Nucleus	
Surface visible to Halley Multicolour Camera	$14.2 \times 7.4 \text{ km}^2$
about 25% illuminated 75% silhouetted	
3-dimensional shape irregular “peanut”	$16 \times 7.4 \times 7.4 \text{ km}^3$
Total surface about volume	400 km^2 550 km^3
Albedo	≤ 0.04
Reflectivity from Vega 2 at $\sim 26^\circ$ phase angle	≤ 0.03
Surface: dark (porous), rough, covered with non-volatile crust of high temperature	$> 300 \text{ K}$
Topographic features: hills, crater-like ring structures, valleys	
Activity concentrated in dust jets, on about 20% of illuminated hemisphere	
Low density	$\leq 500 \text{ kg m}^{-3}$

any case, the formation out of subnuclei requires the relative speed of these nuclei to be small, not more than a few metres per second since low density bodies are fragile.

The concentration of the activity which was restricted to about 20% of the illuminated surface was a surprise. Most of the surface must be covered by a crust or mantle of non-subliming material that was heated to 350 or 400 K [61] during the flybys. These temperatures were much higher than the equilibrium temperature for subliming water ice of about 200 K.

Several surface features of the nucleus are enlarged and displayed in Figure 3. One of the more remarkable features was the ‘crater’, a roundish structure of about 2000 m diameter situated near the limb illuminated by the Sun. It could be a region of past or present (not yet activated by the Sun at the time of imaging) enhanced activity. It was shallow, less than 200 m deep. Another feature was the ‘mountain’ extending above the best fit ellipsoid by 500 to 1000 m. Its peak was illuminated by the rising Sun. Even more remarkable was the sharp, almost rectangular corner of the dark limb located diagonally away from the sub-solar point. This ‘ducktail’ extended about 30% above the ellipsoid. Although the overall shape of the nucleus appeared smooth, several large protrusions could be found. In general, the nucleus looked rather evolved.

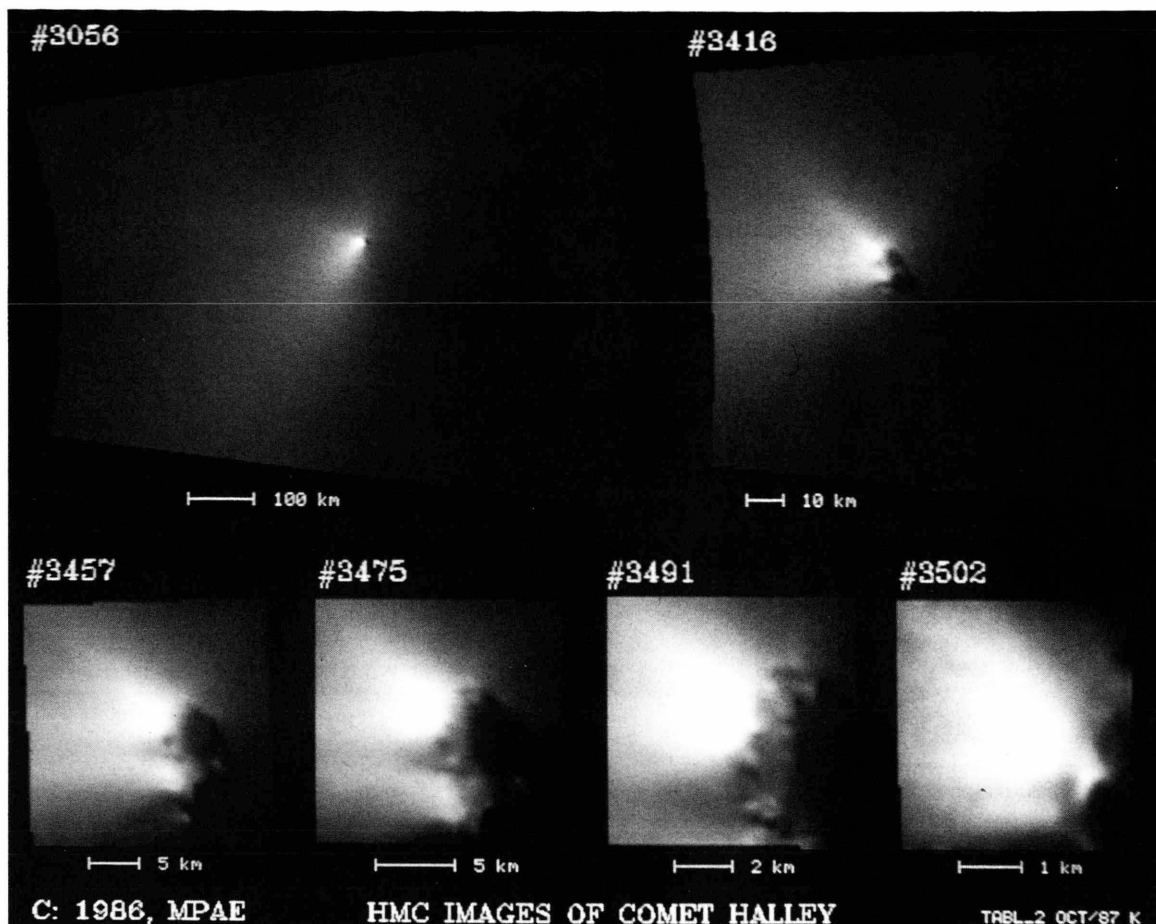
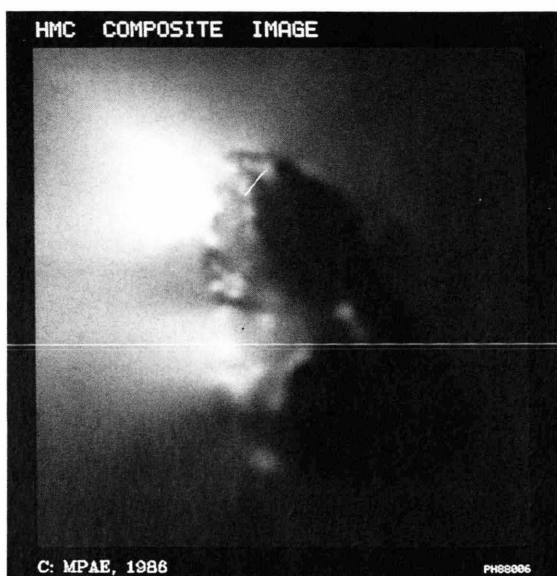


Fig. 1. Six samples of HMC images of P/Halley in original frame sizes. Image # 3056 was taken 1814 s (distance to nucleus 124.000 km) and image # 3502 was taken 31 s (2200 km) before closest approach.



The scale length of the smaller features (like the 'chain of hills') was typically 1/2 to 1 km. Considerable variations of the surface brightness were neither found on the Giotto images [62] nor on images [60] of the Vega spacecraft taken at small phase angle. The reflectivity on HMC images was in the range of 0.5% with a local variation of about 50%. Most of this variation was probably due to topography rather than to changes of the morphology. There seems to be hardly any difference in brightness between active and inactive areas. The conclusion is that the crust and the interior of the nucleus look alike, in other words, the crust is composed of the same material as the non-vol-

Fig. 2. A composite of six HMC images ranging in resolution from 320 m to 60 m per pixel. Illumination by the Sun is from the left, about 28° above the horizontal and 12° behind the image plane.

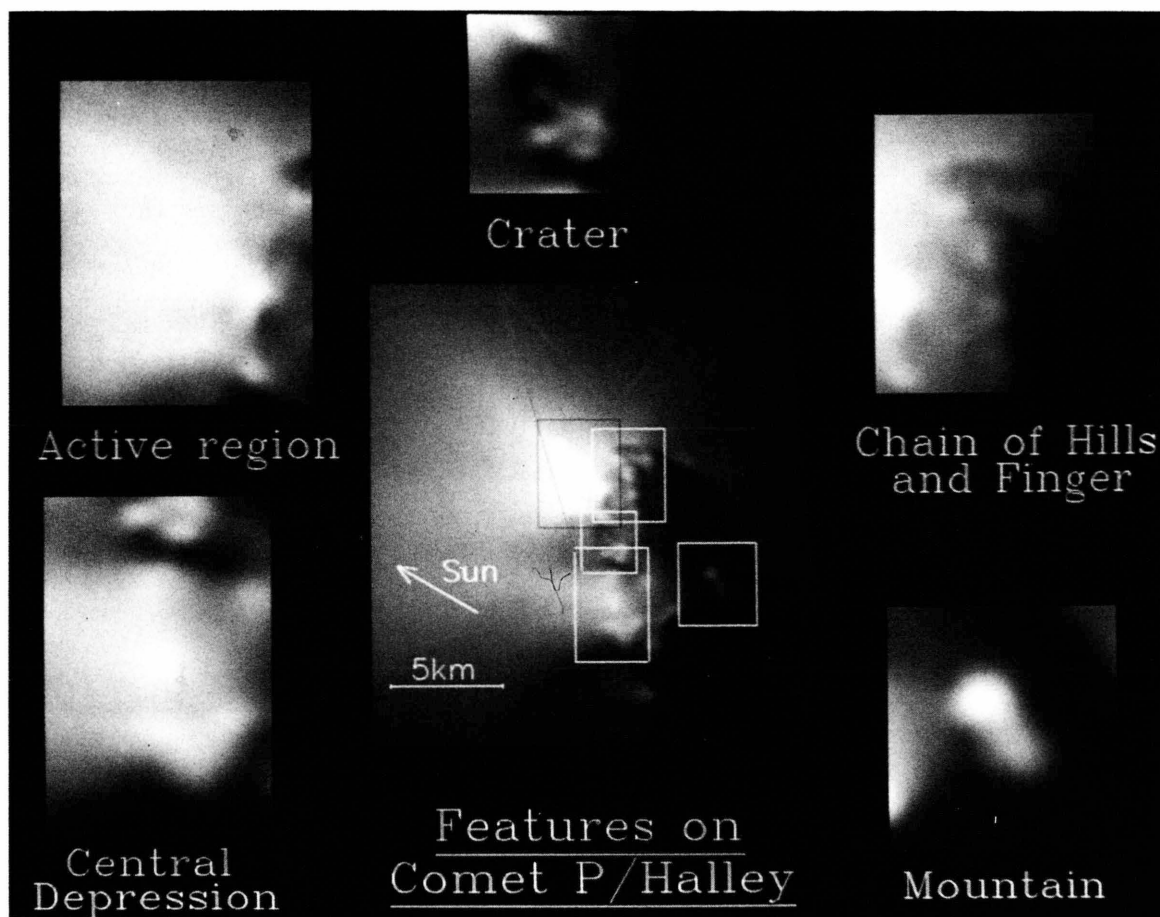


Fig. 3. Features of the comet nucleus are displayed in the cutouts that are expanded by a factor of three.

atile matrix of the nuclear interior. This depleted layer should be thick since it formed the 'mountain' and the 'ducktail'. These protrusions were insulated from 3 sides and did not sublime. They probably consist of depleted matrix material of the nucleus. The matrix was not the ice but rather the non-volatile "dust" material that harboured the ice in the inner parts of the nucleus.

Model calculations [63, 64] of the sublimation process of ice-dust mixtures have shown that a thin crust of 10 to 100 times the typical particle dimension suffices to suffocate the sublimation. To rekindle the activity it is necessary to blow off this thin mantle at the next perihelion passage of the comet, otherwise it becomes dormant [65]. This mechanism cannot maintain small areas of activity over several orbital revolu-

tions. A thick crust (or depleted layer) with some irregularities is suggested. This crust should possibly store some of the heat and, in this way, support slight activity on the nightside of the nucleus. A few narrow dust jets appear to originate on the unilluminated part of the nucleus [66].

It must be considered that comet Halley is the most active short period comet observed so far. However, only about 10 to 20% of its surface was active during the spacecraft flybys. It has not shown any noticeable decay in its activity over the last 30 observed apparitions. Therefore it must be concluded that this restricted activity can be maintained over long intervals of the lifetime of the nucleus. Other short period comets have even smaller parts of their nucleus surface active, of the order of one percent or less. Recently, the

size of a few cometary nuclei could be estimated from ground-based observations (P/Tempel 2 [67], IRAS-Araki-Alcock [68], see also [69]). They are all large and very dark, similar to comet Halley. At close range, cometary nuclei do not appear active at all. The locally concentrated activity is probably characteristic of new comets as well. Assuming an albedo of the nucleus, one can estimate the percentage of the active area from the gas (water or OH) production rates near the Sun and the brightness of the nucleus at large heliocentric distances. The former quantity is proportional to the albedo and the size of the active area, the latter is proportional to the size of the nucleus and its albedo. Size and percentage of the active area can be determined in a similar way as suggested by [70]. The nature of cometary nuclei and of the physical processes that govern them must conform to the steady but restricted activity of comets.

Conclusions from the Observations of Comet Halley

Structure and composition of cometary nuclei are more complex than conceived before the Halley encounters. The low density suggests a high porosity and intricate structure of the bulk material. Its cohesiveness (tensile strength) could be influenced by large amounts of organic materials. Cometary nuclei do not look like the subliming snowballs originally suggested by Whipple [71]. They are not dirty iceballs but may rather be icy dirtballs. The non-volatile ("dust") component plays a more prominent role and may outweigh the volatile (icy or gas) component. The very fluffy dust component may form the matrix out of which the fragile nucleus consists. In the interior of the cometary nucleus the cavities of the dust matrix may be covered and partially filled by ice. A mineral (silicate) structure is coated with organic semi-volatile material that was created in interstellar space and not during the formation of the cometsimals in the early history of the solar nebula. A gradual transition from non-volatile to volatile compounds was observed. The classical notions of cometary gas and dust have changed. The abundances of most elements appear to be similar to those found in the Sun. Cometary material contains larger portions of volatile compounds as compared to carbonaceous chondrites. It is the most pristine material accessible to investigations. The temperature of the nucleus could not have surpassed 50 K since its formation from large subnuclei, requiring low relative speeds of these bodies.

The results of the observations (of which a major contribution comes from the ground-based observational programme, International Halley Watch) strengthen the evidence that comets are indeed members of the solar system and, hence, give important information about the physical conditions and chemical composition during the formation of the solar system. Because of their relative pristine composition they yield information on volatile compounds not found elsewhere. The observed structure and shape of the nucleus of comet Halley support the idea of small planetesimals [72] as the primary building blocks that coalesced from the dust of the presolar nebula. Their number density in the outer planetary system (at or beyond Neptune) had to be high and their relative speed low enough to form larger bodies (the cometary nuclei) without being destroyed by impact or even strongly heated. After the Halley encounters it is more clear that comets may carry direct evidence of the material that formed the solar nebula. The investigations of cometary material under laboratory conditions (via sample return missions) will open the door to a detailed understanding by comparing and assimilating all the information we have acquired from the small bodies and planets in our solar system.

Prospects of the Future

The observations of comet Halley have confirmed that comets provide the most direct access to the physical conditions and processes during the formation of the solar system. However, more insight is needed and will be achieved in future missions to comets. The Giotto Extended Mission (GEM) will reconnoitre an additional short period comet if the spacecraft and its payload are still operational. This mission will address the important question, is Halley a typical comet?

The next step in our exploration of comets is the Comet Rendezvous Asteroid Flyby (CRAF) mission that is currently under development as a joint US/Germany venture. It will allow a longterm study and analysis of a cometary nucleus and its surrounding environment in detail during inactive and active periods.

The physics of comets is of such high scientific merit that the European Space Agency has chosen a comet nucleus sample return mission as one of the cornerstones of the mandatory scientific programme. The preparation of this mission, called Rosetta, is under

way in collaboration with NASA. The launch of this mission that will bring pristine cometary material to laboratories on Earth is scheduled before the end of this century.

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