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The morphology of cometary nuclei

The sudden appearance of a bright comet stretching over a large part of the night sky must have been one of the most awesome phenomena for early humans watching the sky. The nature of comets remained obscure well into the Middle Ages. Only with the introduction of astronomical techniques and analyses in Europe was the parallax of a comet determined by Tycho Brahe for the first time. He proved that comets are not phenomena of the Earth's atmosphere but are farther away than the Moon; in other words they are interplanetary objects. Later Kepler first predicted that comets follow straight lines, then Hevelius suggested parabolic orbits roughly a hundred years later. It was Halley who suggested that the comets of the years 1531, 1607 and 1682 were apparitions of one and the same comet that would return again in 1758. The success of this prediction made it clear that comets are members of our Solar System.

While it was now established that periodic comets are objects of the planetary system, their origin and nature continued to be debated. Were they formed together with the planets from the solar nebula (Kant) or were they of extra-solar origin as suggested by Laplace? This debate lasted for 200 years until well into the second half of the last century. Öpik (1932) suggested that a cloud of comets surrounded our Solar System. This hypothesis was quantified and compared to the observed distribution of orbital parameters (essentially the semi-major axes) of new comets by Oort (1950) (Section 2.1). Comets are scattered into the inner Solar System by perturbations caused by galactic tides, passing stars and large molecular clouds.

The Oort cloud would have a radius of 2×10^5 AU, a dimension comparable to the distances of stars in our neighbourhood. The lifetime (limited by decay due to activity and by perturbations caused by encounters with planets) even of the new comets on almost parabolic orbits and typical periods of the order of 10^6 years is short compared to the age of the planetary system (4.5 Gy). Therefore, observed comets could only recently have arrived on their orbits dipping inside the inner Solar System.

This reservoir of comets must have been established during the formation process of the planetary system itself. Cometesimals were agglomerated from interstellar/interplanetary gas and dust and scattered out of the inner Solar System by the giant outer planets (Section 2.3). This scheme implies that a central part of a comet, its nucleus, is stable enough to survive these perturbations. It must also be stable enough to pass the vicinity of the sun for many times in the case of a short-period comet.

Comets are bright and large when they are close to the sun and fade quickly when they recede beyond about 2 AU. Only with the advent of photography and large astronomical telescopes could a comet be followed until it becomes a star-like point source. What makes comets active near the Sun, blowing their appearances up to the order of 10^5 km? Bright comets often develop tails two orders of magnitude longer.

In an attempt to explain the cometary appearance, Bredichin (1903) introduced a mechanical model where repulsive forces drive the particles away from a central condensation. Spectroscopy revealed that dust grains reflect the solar irradiation. In addition, simple molecules, radicals and ions were found as constituents of the cometary coma and tail. The nature of the central condensation remained mysterious for a long time because of the observational dilemma. When the comet is close to the Earth and therefore to the Sun the dense coma obscures the view into its centre. When activity recedes the comet is too far away and too dim for detailed observations of its central condensation. During the middle of the nineteenth century the connection between

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comets and meteor streams was established. Schiaparelli (1866) calculated the dispersion of cometary dust within the orbital plane. From this time on the perception that the central condensations of comets were agglomerations of dust particles prevailed for about a century. The gas coma was explained by desorption of molecules from dust particles with large surfaces (Levin 1943). The storage of highly reactive radicals (most observed species (CN, CH, NH_2, etc.) were of this category) posed a major difficulty to be explained. The inference that these radicals should be dissociation products of stable parent molecules (such as $(CN)_2$, CH_4, NH_3, etc.) by Wurm (1934, 1935, 1943) led to our present understanding that these molecules are stored as ices within the central nucleus of a comet. Whipple (1950a,b) combined the astrometrical observations of changes of the orbital periods of comets with the existence of an icy cometary nucleus. The sublimation of ices cause reactive (rocket) non-gravitational forces that increase or decrease the orbital period of an active comet according to the sense of rotation of its nucleus.

Evidence in support of the icy conglomerate nucleus became more and more compelling by the derived high gas production rates that could not be stored by adsorption on dust grains (Biermann and Trefftz 1964, Huebner 1965, Keller 1976a,b) and by the same account by the large quantities of dust moving into the cometary tail (Finson and Probstein 1968b). The ‘sand bank’ model (Lyttleton 1953) was clearly dismissed in favour of a solid icy nucleus. Its formation and origin could now be explored.

While there was some knowledge about the chemical composition of the nucleus, its physical properties, even the basic ones like size, shape and mass, remained largely unknown because the nucleus could not be observed. Early attempts to derive the nucleus size from the ‘nuclear’ magnitudes of comets at large heliocentric distances while they are inactive (Roemer 1966a,b) led to a systematic overestimation of the size because their residual activity could not be eliminated.

The advent of modern detectors and large ground-based telescopes revealed that most comets display residual activity or clouds of dust grains around their nuclei. Taking the residual signal into account (mostly using simple models for the brightness distribution) the size estimates of the nuclei could be improved. The (nuclear) magnitude of a comet depends on the product of its albedo and cross-section. Only in a few cases could the albedo and size of a cometary nucleus be separated by additional observation of its thermal emission at infrared wavelengths. By comparison with outer Solar System asteroids Cruikshank *et al.* (1985) derived a surprisingly low albedo of about 0.04. A value in clear contradiction to the perception of an icy surface but fully confirmed by the first resolved images of a cometary nucleus during the flybys of the Vega and Giotto spacecraft of comet Halley (Sagdeev *et al.* 1986, Keller *et al.* 1986).

The improvements of radar techniques led to the detection of reflected signals and finally to the derivation of nuclear dimensions and rotation rates. The observations, however, are also model dependent (rotation and size are similarly interwoven as are albedo and size) and sensitive to large dust grains in the vicinity of a nucleus. As an example, Kamoun *et al.* (1982) determined the radius of comet Encke to 1.5 (+2.3, −1.0) km using the spin axis determination of Whipple and Sekanina (1979).

The superb spatial resolution of the Hubble Space Telescope (HST) is not quite sufficient to resolve a cometary nucleus. The intensity distribution of the inner coma, however, can be observed and extrapolated toward the nucleus based on models of the dust distribution. If this contribution is subtracted from the central brightness the signal of the nucleus can be derived and hence its product of albedo times cross-section (Lamy and Toth 1995, Rembor 1998, Keller and Rembor 1998; Section 4.3).

It has become clear that cometary nuclei are dark, small, often irregular bodies with dimensions ranging from about a kilometre (comet Wirtanen, the target of the Rosetta comet rendezvous mission) to about 50 km (comet Hale-Bopp, comet P/Schwassman-Wachmann 1). Their albedos are very low, about 0.04. Their shapes are irregular, axes ratios of 2:1 are often derived. Even though comets are characterized by their activity, in most cases only a small fraction of the nuclear surface (in some cases less than 1%) is active. An exception seems to be comet P/Wirtanen where all its surface is required to be active in order to explain its production rates (Rickman and Jorda 1998). The detection of trans-Neptunian objects (TNOs) in the Kuiper belt (Jewitt and Luu 1993) reveals a new population of cometary bodies with dimensions an order of magnitude bigger (100 km and larger) than the typical comet observed in the inner planetary system. Little is known about the extent, density, size distribution and physical characteristics of these objects. This region is supposedly the reservoir for short-period comets, manly those controlled by Jupiter (Jupiter family comets).

Our present concept of a cometary nucleus has been strongly influenced by the first pictures of the nucleus of comet Halley achieved during the Giotto flyby in 1986. While this revelation seems to be confirmed as typical by modern observations it carries the danger of prototyping new observational results and inferences. Missions and spacecraft are already on their way (Deep Space, Contour, Stardust, Deep Impact) or in preparation (Rosetta) to diversify our knowledge.

The morphology of cometary nuclei is determined by their formation process in the early solar nebula, their dynamics and evolution. The physics of the processes leading to their apparent activity while approaching the Sun are still obscure in many details but determine the small- and intermediate-scale morphology. The large-scale morphology, the shape, of a cometary nucleus is determined by its fragility and inner structure and by its generally complex rotational state. These topics will be reviewed in the following sections. Chemical and compositional aspects will be only discussed where they are important in the framework of the physical evolution of cometary nuclei. More details are given in Chapter 53. A brief survey of the current modelling efforts is given. The fate of cometary nuclei and their decay products follows. A summary and outlook ends this chapter on the morphology of cometary nuclei.

1 FROM DUST TO COMETS

1.1 Planet formation in the early Solar System

In Whipple's icy conglomerate model of a cometary nucleus, the ices were mixed with differentiated refractory matter deduced by analogy to meteoritic materials. The nucleus could be quite inhomogeneous, and large refractory boulders or even a refractory core were conceivable (Sekanina 1972). About 20 years after Whipple's model of a solid nucleus the concept that planet formation was triggered by gravitational instabilities of the dust component of the rotating solar nebula made comets to become building blocks of the planetary system. The growing dust grains settle towards the centre plane of the rotating disk until the density reaches a critical value where gravitational instability occurs (Safronov 1969, Goldreich and Ward 1973). The timescales for formation of these building blocks are short: 10^5 to 10^6 years. The size distribution of the resulting nuclei could be estimated based on the scale lengths for the gravitational instability to a few kilometres (Biermann and Michel 1978). Once a larger body is formed it grows very fast by gravitationally attraction (gravitational runaway) to form a planet. The ices of the cometary volatile components (predominantly water) require formation of the comets outside Jupiter's orbit. The sizes of the homogenous cometary nuclei remain small enough that gravitational compaction is unimportant and the grains from the molecular cloud are hardly altered. The degree of processing of these grains before they agglomerate depends on the physical parameters of the molecular cloud at the location of planetesimal formation such as the optical depth (shielding the dust from the central early Sun) and the resulting local temperature. A conceivable extreme is the formation directly from interstellar grains (Greenberg 1977, 1998).

1.2 Accreation of building blocks

In contrast to the formation of comets by gravitational instabilities, Weidenshilling (1995) shows that for plausible parameters of the solar nebula the presence of gas induces drag forces on the dust particles and prevents local gravitational instability. Submicrometre- to micronmetre-sized particles entrained in the gas of the contracting solar nebula grow by coagulation due to Brownian motion and settle toward the central plane. The larger grains decouple from the gas motion and sweep up the smaller grains to grow fast to centimetre sizes. This growth is based on interlocking molecular forces. Before the particles reach the critical density for gravitational instability to occur they would decouple from the gas and follow Keplerian orbits. The presence of the gas still influences the motion of the particles by inducing a drag force that is size dependent. The differential rotation relative to the gas causes shear forces that induce turbulence preventing the grain density increasing further (Weidenshilling 1980, Cuzzi *et al.* 1993). Thus cometesimals cannot form by collapse of a cloud of centimetre-sized particles but they have to grow by coagulation and agglomeration to metre size before they decouple from the shear-induced turbulence. But growth does not stop there because the gas drag-induced radial velocity dispersion decreases relatively fast for larger bodies (Figure 1). Once they reach dimensions of tens or hundreds of metres gas drag becomes insignificant. The lag of damping prevents local gravitational collapse to form solid planetesimals (Weidenshilling 1995).

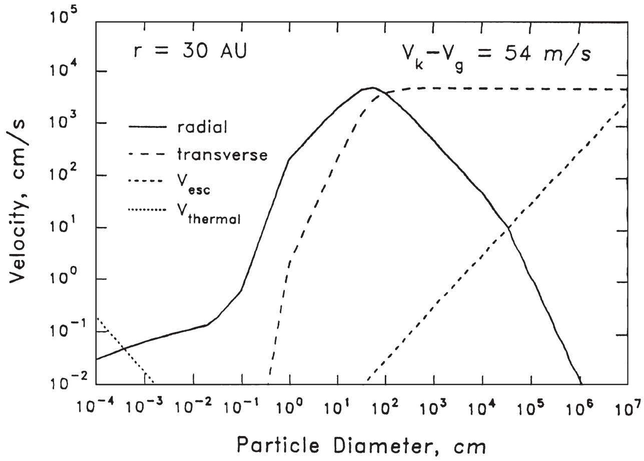

Figure 1 Particle velocities as a function of size in the model nebula at 30 AU. Particles are assumed to have a fractal structure at size 10^{-2} cm, and constant density of 0.7 cm^{-3} at $d > 1$ cm. Dotted line: thermal velocity at $T = 50$ K. Solid line: radial velocity, with peak value equal to $\Delta V = 54\, cm\, s^{-1}$ at $d \approx 10^2$ cm. Changes in slope are due to variation of particle density ($d \leq 1$ cm) and transition from Epstein to Stokes drag law ($d \approx 10^5$ cm). Dashed line: transverse velocity relative to pressure-supported gas. Short dashed: escape velocity from the particle's surface. (From Weidenshilling 1997.)

The radial velocity distribution as a function of particle size controls the evolution of the growing bodies. Figure 1 depicts a typical scenario in the solar nebula at a radial distance of 30 AU from the Sun (Weidenshilling 1997). Small particles rotate with the gas velocity but drift radially inward, while large particles follow Keplerian orbits and plough through the slower rotating gas. The peak velocity is reached for particle sizes for which the drag-induced response time $t_e = mv/F_D$ (m is particle mass, v is relative velocity and F_D is drag force) is comparable to the orbital period at the radial distance in question. This velocity distribution controls the agglomeration of the bodies. As long as gravitational attraction is unimportant the large bodies grow relatively slowly because of their small velocities. They typically grow from bodies at factors 3 to 5 times smaller that still have higher speeds. For example, after 8×10^4 s the largest bodies of 70 m accrete from 20 m 'particles'; at 1.5×10^5 s, 500 m from 200 m; at 2×10^5 s, 6 km from 1 km. Now the velocity becomes gravity influenced and at 2.5×10^5 s, 80 km bodies are growing by gravitational accretion. At any given time most of the mass is concentrated in a narrow size range.

1.3 Dust coagulation

These model calculations obviously require the dust particles to coagulate, to stick to each other at velocities up to several metres per second and agglomeration to prevail over destruction for metre-sized bodies at speeds of $50\,\mathrm{m\,s^{-1}}$. Then the typical timescales for formation of cometesimals is a few thousand orbital periods so that comets could form within 10^6 years even in the Kuiper belt at 40 or 50 AU.

The formation of cometesimals by coagulation implies that the bodies are physically not homogenous but built of subnuclei of various sizes and typically about 3 to 10 times smaller than the body itself. Theses subnuclei themselves show a similar structure relative to their overall size. The speed of collisions are high enough that the building blocks may be partly shattered or have penetrated each other. The details will depend on physical parameters such as density, fluffiness (fractal dimension), stickiness, tensile strength, and so on. These parameters will vary as a function of body size. One expects voids between building blocks and volumes of increased density where penetration took place.

The timescale for accretion and the considerable radial velocities of the bodies imply radial migration over substantial heliocentric distances. Origination of particles from different heliocentric distances at different times during the formation of a cometesimal could lead to chemical differentiation, in particular in the dust to gas ratio.

2 RESERVOIRS OF COMETS

2.1 The Oort cloud

Comets are rather artificially divided into two classes, the short-period (SP) comets with orbitial periods of less than 200 years and the long-period (LP) comets. The activity of comets near the Sun removes about 0.1 to 1% of the mass of the nucleus per orbit, so that the lifetime of a cometary nucleus is less than 1000 orbital periods. Obviously even LP comets with orbital periods of 10^6 years would not have survived on their present orbits from the beginning of the Solar System. Consequently comets are either formed or captured episodically. If of primordial origin they could not have formed on their present orbits. Hypotheses based on episodical events include gravitational focusing of passing interstellar cloud material (Lyttleton 1948), compression of interstellar clouds by shocks (McCrea 1975), or formation in giant molecular clouds and subsequent capture by the Solar System (Clube and Napier 1982) or even formation by eruption of the giant planets and their satellites (Vsekhsvyatskii 1967). These ideas have found little support.

Oort (1950) analysed the distribution of orbital energies of new (LP) comets, characterized by $1/a$ where a is the semi-major axis of the orbit. The more recent compilation by Marsden (1989b) shown in Figure 2 confirms the very strong peak with $1/a < 10^{-4}\,\mathrm{AU}^{-1}$. New (in the dynamical sense) comets come from distances almost comparable to the distances of nearby stars. Once penetrating the inner Solar System their orbits are strongly perturbed mainly by Jupiter with $\Delta(1/a) \approx \pm 6 \times 10^{-4}\,\mathrm{AU}^{-1}$ (Everhart 1968) and rapidly diffuse to small semi-major axes if not expelled from the Solar System. Only a minute fraction ($<10^{-3}$) of these new comets will become SP comets, not enough by far to explain the presently known SP comets (about 600; Williams 2000). To explain the few (less than 10 per year) observed newly detected comets the spherical reservoir of randomly distributed comets must entail more than 10^{12} (Weissmann 1980) comets. Oort demonstrated that passing stars perturb the cloud of comets repeatedly and change the velocities of the comets (change of momentum) but change their orbital energies very little. Most of the comets, therefore, stay bound to the Solar System even though their orbital energies are very small. The probability of a comet in the Oort cloud being directed into the inner Solar System ($<$30 AU) is controlled by the very small solid angle the inner Solar System encompasses seen from the fringes of the Solar System at about 10^5 AU.

2.2 The Edgewood–Kuiper belt and TNOs

While Oort's hypothesis explains the currently observed numbers of new and LP comets it does not account for the http://www.springer.com/978-0-7923-7196-0

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