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Origin and Evolution of Cometary Nuclei

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Abstract One of the key goals of the Rosetta mission was to understand how, where and when comets formed in our solar system. There are two major hypotheses for the origin of comets, both pre-Rosetta: (1) hierarchical accretion of dust and ice grains in the Solar Nebula and (2) the growth of pebbles, which are then brought together by streaming instabilities in the Solar Nebula to form larger bodies. Rosetta provided a wealth of new information on comet nuclei and confirmed many past ideas on comets, e.g., high volatile content, lack of aqueous alteration of grains, and the low bulk density of the nucleus. Rosetta also provided new data on the nature of cometary activity, the active geology on the nucleus surface and the interior structure and bulk density of the nucleus. Supporters of the above-mentioned origin hypotheses each find confirmation of their ideas in the Rosetta results. But the question of which hypothesis is preferred, or if there are other, better hypotheses that could be invoked, could not be answered. Theoretical studies suggest that comet nuclei were collisionally processed in the Primordial Disk though it is not clear that the nuclei we see today display the effects of that process. Both theoretical and observational studies suggest that the major end-states for cometary nuclei are dynamical ejection, random disruption and disintegration, and/or evolution of nuclei to inactive, asteroidal-appearing objects. Rosetta has provided us with many new insights that will help to guide future cometary missions, observations, experiments and theoretical investigations that will lead to answers to the fundamental questions with regard to cometary origin.

Keywords Comet, origin · Hierarchical accretion · Agglomeration · Pebbles · Streaming instabilities · Evolution · End-states · Primordial disk · Collisional evolution

Comets: Post 67P / Churyumov-Gerasimenko Perspectives
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1 Introduction

Comets are among the most primitive bodies in the solar system. They likely formed at large solar distances where volatile ices could condense and remain stable, and they retain a cosmo-chemical record of the composition of, and the processes in, the Solar Nebula when the planets were forming. Comets have been stored in cold, distant orbits, either in the Kuiper belt region (Kuiper 1951) at ∼35–100 AU, where the mean temperature is ∼40 K, or in the Oort cloud at $\sim 3\text{–}150 \times 10^3$ AU (Oort 1950) where the mean temperature is ∼10 K. Note that the Kuiper belt region contains two distinct dynamical populations. The first is the Classical Kuiper belt at ∼35–100 AU, with objects in low eccentricity, low inclination orbits beyond Neptune (Duncan et al. 1988). The second is the Scattered disk at $\sim 30\text{–}\sim 10^3$ AU (Duncan and Levison 1997; Levison and Duncan 1997) consisting of objects with perihelia close to Neptune's orbit but with larger orbital eccentricities, inclinations and aphelia than the Classical Kuiper belt. The Scattered disk is the source of most of the Jupiter-family comets (JFCs).

The primitive and cold nature of cometary nuclei is confirmed by the highly volatile ices that are released when the nuclei come close to the Sun. These include: CO ice with a sublimation point, $T = 25$ K; CH_3OH ice, $T = 99$ K; and CO_2 ice, $T = 72$ K (corresponding to a saturation density of 10^{13} cm^{-3}; Yamamoto 1985).

Unlike earlier flyby missions, ESA's Rosetta mission (Glassmeier et al. 2007) was designed to be the first truly intensive space mission to a comet, following it from ∼3.6 AU pre-perihelion through perihelion at 1.24 AU and out to ∼4 AU post-perihelion—over a period of more than two years. The target comet, 67P/Churyumov-Gerasimenko (hereafter, 67P), is a typical Jupiter-family comet, though it proved far more interesting than anyone had expected. The mission yielded a wealth of data that is only now beginning to be fully digested and analyzed.

One of the key questions that Rosetta wanted to answer is how, where and when did comets form? The known presence of substantial volatile ices in cometary nuclei showed that the formation zone(s) had to be, at a minimum, moderately far from the Sun, beyond the so-called "snowline" where ices would be stable. In the present solar system that distance is taken to be 3–5 AU but in the dusty Solar Nebula it may have been closer to (or farther from) the Sun (Sasselov and Lecar 2000; Min et al. 2011).

For a long time the generally accepted hypothesis for comet (and asteroid and planet) formation was hierarchical accretion (Weidenschilling 1977, 1997). Grains of micron-sized dust and ice were expected to collide in the Solar Nebula and stick, leading to larger and larger particles. This led Donn and Hughes (1986) to propose the *fractal aggregate* model in which hierarchical accretion continued to occur at all size scales, leading to an irregular nucleus perhaps kilometers in diameter. A similar model was proposed by Weissman (1986), based more on phenomenological observations of comets, such as outbursts and splitting events, the *primordial rubble pile*. In Weissman's model the final stages of accretion led to kilometer-sized nuclei but there was no energy sources to mold this primitive material into a single coherent body. However, studies of hierarchical accretion had problems in growing particles larger than ∼1 meter (Weidenschilling 1977, 1997). Particles might begin to bounce off one another, or to be collisionally eroded and disrupted. How could proto-nuclei grow beyond this size range?

In 2005 Youdin and Goodman proposed a different scenario. They argued that hierarchical accretion would lead to dust aggregates on the order of 1 cm in size; these particles have come to be known as "pebbles." Streaming (hydrodynamic) instabilities in the Solar Nebula would bring the pebbles together until they gravitationally coalesced into larger bodies on the order of 100 km in diameter. However, this result was also problematic because such large bodies would be warmed internally by short-lived radio-nuclides such as ^{26}Al, leading to temperatures that would have driven off many of the more volatile ices seen in comets (Prialnik et al. 1987; Merk and Prialnik 2003). Also, internal pressures in 100-km nuclei would lead to compaction and possible destruction of the micron-sized agglomerates collected by Rosetta (Merouane et al. 2016) and seen in Interplanetary Dust Particles (IDPs, Brownlee 1985), which are believed to have a cometary origin.

In this paper we will review the arguments for and against the two leading formation mechanisms and discuss what new information the Rosetta results have brought to this issue. In Sect. 2 we review hierarchical accretion while in Sect. 3 we cover accretion of pebbles in streaming instabilities. Section 4 presents a discussion of collisional processes in the Solar Nebula and the early solar system. Sections 5 and 6 are brief discussions of the evolution of cometary nuclei and the likely end-states for cometary nuclei, respectively. Finally, in Sect. 7 we discuss all these issues and suggest ways that they can be addressed by future space missions to comets, as well as by ground-based observations and laboratory and theoretical studies.

2 Comet Nucleus Formation Through Hierarchical Agglomeration

In this section we describe the dynamical aspects of hierarchical agglomeration (Sect. 2.1), the internal structure expected for bodies formed by hierarchical agglomeration (Sect. 2.2), and how these expectations compare with observations of 67P and other comets (Sect. 2.3).

2.1 Dynamics of Hierarchical Agglomeration

Hierarchical agglomeration is the gradual merging of smaller bodies (cometesimals) through gentle hit-and-stick collisions where gravity has little to no influence on the formation of bodies smaller than ∼10 km (Weidenschilling 1997). At larger sizes gravity-assisted accretion becomes increasingly important. In order for collisions to occur, bodies of different sizes need non-zero relative velocities with respect to each other. In the Solar Nebula this is caused by gas drag which promotes mergers between bodies that differ greatly in size (e.g., Adachi et al. 1976; Weidenschilling 1977). In the Primordial Disk, the collection of planetesimals left behind when the gas in the Solar Nebula is dissipated after ∼3 Myr (Zuckerman et al. 1995; Haisch et al. 2001; Sicilia-Aguilar et al. 2006), this is caused by viscous stirring (excitation of low-mass body orbits by more massive bodies), which allows for mergers between bodies of any size ratio. This means that hierarchical growth changes character as the Solar Nebula evolves into the Primordial Disk.

Detailed accounts for the dynamics of hierarchical agglomeration are found in, e.g., Weidenschillling (1977, 1997), Kenyon and Luu (1998), and Windmark et al. (2012a, 2012b). Davidsson et al. (2016) proposed a two-step hybrid scenario where streaming instabilities first create pebble swarms that collapse gravitationally to form $D > 50$ km bodies (see Sect. 3). Since this population would later grow into Pluto-sized objects they were referred to as "TNOs". When the number density of remaining pebbles falls below ∼15% of the initial value the pebble swarms can no longer reach the Roche density needed for gravitational collapse. This growth phase lasts $\sim 10^3$ yr (Johansen et al. 2007). At that point a second growth mode sets in where small comet nuclei are built slowly through hierarchical agglomeration. The slow growth means that heat produced by ^{26}Al is dissipated from these small bodies without modifying the composition or the physical structure of the forming

Table 1 Growth time scales, target/projectile diameters, and relative velocities in hierarchical growth

Time t (Myr)	D (m)	d (m)	v_{rel} (m s^{-1})
0.1	0.1	4×10^{-6}	10
0.3–0.6	1	0.01–0.1	30
0.35–0.7	7	2–3	2
0.4–0.8	70	20	0.8
1.2–2.4	500	200	0.2
1.7–3.6	6,000	1,000	2

cometesimals. Because the bodies quickly grow larger than the ∼1 cm diurnal thermal skin depth, into 10–100 m bodies, most of the ice is kept at substantially lower temperature than experienced by pebbles, facilitating the preservation of volatiles. Growth to the final size would have to proceed at a much slower rate to avoid radiogenic heating.

Davidsson et al. (2016) proposed the time scale of growth shown in Table 1, where D is the diameter of bodies being formed, d is the diameter of the smaller bodies being primarily consumed, and v_{rel} is the relative velocity during collisions, taken from Weidenschilling (1997). Here $t=0$ is the formation time of CAIs (calcium-aluminum inclusions), taken to coincide with the transition from a Class 0 to Class I protostar; the protosun would reach its final mass and the Solar Nebula (last remains of the accretion disk) would be born at $t\sim10^5$ yr (Andre and Montmerle 1994; Montmerle et al. 2006). The ranges in t reflect differences in growth rates at 15 AU (faster) and 30 AU (slower).

An important feature of Table 1 is the peak in the relative velocity, $v_{\text{rel}}=30$ m s^{-1}, reached when growing bodies are a few meters in diameter. This is because meter-sized bodies, which have very slow radial drift velocity at 15–30 AU, primarily consume cm-dm sized bodies that have the highest radial drift velocities at these heliocentric distances (Weidenschilling 1997). It is therefore expected that the highest level of compaction (porosity ∼60%) and therefore the strongest and most resilient structures in these nuclei have diameters of a few meters. Also, note that $d \ll D$ which means that these are single-lobe objects. The expected bulk density is in the range 200–400 kg m^{-3}, while the meter-sized compact building blocks have densities of 300–700 kg m^{-3} (Davidsson et al. 2016).

At the end of the Solar Nebula lifetime the vast majority of hierarchically grown objects are small with $D=0.1$–1 km. However, growth continues in the Primordial Disk under new conditions. Davidsson et al. (2016) estimate that the average v_{rel} increases from 2 m s^{-1} to 40 m s^{-1} in the first 25 Myr because of viscous stirring, and it is not uncommon that similarly sized nuclei collide. This is therefore an era of adding a more compact outer shell to each body, pushing the bulk densities towards ∼500 kg m^{-3}, and merging objects into bilobate nuclei. After 25 Myr have passed the largest hierarchically grown nuclei have $D\sim$ 50 km and because of mergers and accretion onto the population of large previously formed TNOs the number density of comet nuclei is small enough to avoid substantial collisional processing even when v_{rel} becomes destructive. However, if the disk mass was higher than assumed by Davidsson et al. (2016) the initiation of collisional grinding may be unavoidable.

2.2 The Internal Structure of Hierarchically Grown Bodies

What does a body grown through hierarchical agglomeration look like? The low v_{rel} in Table 1 led some researchers to suggest that they would be highly porous structures with large internal voids, such as the *fractal aggregate model* of cometary nuclei proposed by Donn and Hughes (1986). The *primordial rubble pile model* of Weissman (1986) emphasized local melting and weak bonds at contact surfaces between the building blocks and was illustrated as a non-fractal yet porous and irregular object. See Weissman (1990) for graphical representations (also reproduced in Donn (1991)).

The images of Comet 19P/Borrelly obtained with Deep Space 1 seemed to confirm the primordial rubble-pile concept: "the shape of and structures in the nucleus are proof of its formation by coalescence of multiple bodies," (Soderblom et al. 2002). The discovery of steep walls on 81P/Wild 2 imaged by Stardust, which requires some nucleus cohesion, led Weaver (2004) to question a rubble-pile structure that he (incorrectly) thought of as completely cohesionless. The discovery of pervasive layering on Comet 9P/Tempel 1 in Deep Impact images (Thomas et al. 2007) inspired new concepts and ideas.

Lasue et al. (2009, 2011) performed numerical simulations where 5×10^4 hard spheres (monodisperse or with a size distribution) were allowed to collide, aggregate through sticking, form even stronger bonds over time through sintering, and break apart during collisions or compaction that leads to restructuring. In their view, layering occurs since the cohesive strength distribution becomes organized over time, forming a strong core and gradually weaker shells at larger distance from the center. However, Lasue et al.'s results largely reflect the input assumptions of their model, and the results of their simulations may not be useful. Belton et al. (2007) proposed an alternative view, where layers represent flattened cometesimals that became strongly deformed at impact—this is the *layered pile model* or the "talps" model (the word "splat" spelled backwards).

Davidsson et al. (2016) speculated that the rather high v_{rel} during final accretion in their scenario would break the projectiles and release their most cohesive meter-sized building blocks, which would stand some chance of remaining intact. These small constituents could spread out locally and form a layer of finite size, analogous to the talps model. However, if bouncing takes place (illustrated by the jumping Philae lander) one can imagine that a global "particle atmosphere" forms during a few hours after the impact, before settling to form a global layer.

If so, the interior of comets could be dominated by heterogeneity on the meter-scale. The final merger of the lobes would not result in such disintegration because the impact energy would be dissipated in the deformation zone at the contact area that is small compared to the size of the lobes. de Niem et al. (2018) find that equal-sized planetesimals at kilometer size-scales can hit and stick at velocities as high as $30\ \mathrm{m\,s^{-1}}$. This would not be the case when a small projectile impacts a much larger body. Note that meter-sized heterogeneities in the interior of 67P could not have been detected by the CONSERT radar experiment on Rosetta/Philae because the radar wavelength was 3 meters.

The biggest challenge lying ahead is to model the bodies formed by hierarchical agglomeration realistically in order to produce qualitative predictions that can be compared with observations. The Smoothed Particle Hydrodynamics code applied by Jutzi and Asphaug (2015) and the Backward Euler hydrocode used by de Niem et al. (2018), that can consider low-velocity collisions between highly porous bodies with realistic material parameters, are steps in the right direction. However, such codes need to consider *multiple consecutive* collisions between objects resolved down to the meter-scale at relevant velocities in order to produce model nuclei that better represent hierarchically grown objects.

2.3 Is Hierarchical Agglomeration Consistent with Observed Properties of Comet Nuclei?

Hierarchical agglomeration predicts continuous comet nucleus growth during ~25 Myr (Davidsson et al. 2016). Such long time scales could be consistent with the substantial fraction of crystalline silicates in comets (Kelley and Wooden 2009) originating from the inner

Solar System and gradually mixed out to the comet-forming region during the Solar Nebula lifetime. The presence of chondrule fragments in Stardust samples from 81P/Wild 2 (Nakamura et al. 2008), of which some have an age of at least 3 Myr (Ogliore et al. 2012), is consistent with slow growth. Furthermore, the lack of phyllosilicates in 81P/Wild 2 samples (e.g., Brownlee et al. 2012), the lack of the phyllosilicate 0.7 μm absorption in 67P (except possibly in a handful of small boulders (Oklay et al. 2016), and the absence of amino acids other than glycine in 67P (Altwegg et al. 2016) suggest that these comets did not contain liquid water. If ^{26}Al, with a half life of 7×10^5 years (Norris et al. 1983), was present at large heliocentric distances this means that these comets formed sufficiently late not to become aqueously altered.

The bilobate shapes of 8P/Tuttle (Harmon et al. 2010), 19P/Borrelly (Oberst et al. 2004), 103P/Hartley 2 (A'Hearn et al. 2011), 67P/Churyumov-Gerasimenko (Sierks et al. 2015), and possibly 1P/Halley (Merenyi et al. 1990; Keller et al. 2004) show that low-velocity mergers between similarly-sized cometesimals are common. Although such mergers would not be common in the drag-dominated Solar Nebula (Weidenschilling 1997), they would be common in the gently viscously stirred Primordial Disk (Davidsson et al. 2016). Such nucleus shapes are therefore consistent with hierarchical agglomeration.

The scenario proposed by Davidsson et al. (2016) suggests a higher core porosity (low-velocity growth in the Solar Nebula) and a lower shell porosity (growth in the Primordial Disk at higher velocities) for each lobe. This is consistent with CONSERT observations indicating a 15% decrease of porosity over the top 150 meters in the small lobe (Ciarletti et al. 2015). The low bulk density of 67P, $\rho = 533 \pm 6\ \mathrm{kg\,m^{-3}}$, (Jorda et al. 2016; Pätzold et al. 2016) is consistent with the low comet bulk densities obtained primarily from nongravitational force modeling (e.g., Rickman 1986; Rickman et al. 1987; Weissman et al. 2004; Davidsson and Gutiérrez 2004, 2005, 2006; Davidsson et al. 2007; Richardson et al. 2007; Sosa and Fernández 2009), and the high level of porosity this implies is consistent with low-velocity mergers.

Cometesimals with $D = 2$ and 3 km (similar to the small and large lobes of 67P) are expected to be built by objects with diameters in the 0.3–0.6 km and 0.5–1 km ranges, respectively (Weidenschilling 1997). Structures in the Bastet region on the small lobe shaped as spherical caps with 320–480 m diameter called Positive Relief Features are possible examples of such cometesimals (Davidsson et al. 2016). According to CONSERT observations reported by Kofman et al. (2015): "Two or three well-defined propagation paths could indeed be potentially due to the presence of a large structure inside the nucleus." In addition, the 500-m size "accumulation basins" in Imhotep on the large lobe (particularly F, see Fig. 2 of Auger et al. 2015) with flat floors and raised rims are not high-velocity impact craters. They could be the scars of low-velocity impacts of objects roughly the size of the features. Simulations #18 and #19 by de Niem et al. (2018), where highly porous 1 km objects impact 3 km targets at low velocity (5–13 $\mathrm{m\,s^{-1}}$) appear to show similar morphologies. Or they could be sublimation basins where the walls are active and slowly grow outward as a non-volatile residue is left to form the smooth flat floors of these features.

The widespread layering on 67P (Massironi et al. 2015; Penasa et al. 2017), revealed by intricate systems of terraces carved by sublimation, suggest that the lobes were formed separately and that some sort of accretion process that acted over time was active during their formation. The discovery that the reflectance of the layers decreases systematically with increasing distance from the lobe center (Ferrari et al. 2018) could be the result of gradual accretion of material that changed compositional and/or textural properties over time. These properties are at least conceptually consistent with hierarchical agglomeration (Lasue et al. 2009, 2011; Belton et al. 2007; Davidsson et al. 2016), though we emphasize again that this process needs to be modeled in detail to be fully understood.

Finally, the consolidated terrains on the nucleus of 67P, including walls of pits that extend ∼100 m into the nucleus, are rich in small spheroidal structures called "goose-bumps" (Sierks et al. 2015). Having a typical diameter of 2.5 ± 1 m, they were interpreted by Davidsson et al. (2016) as the most cohesive structures formed during hierarchical agglomeration. However, this interpretation is controversial and it has been suggested (El-Maarry et al. 2015; Auger et al. 2018) that they are thermal contraction crack polygons further evolved by sublimation. The two views may coexist in case fractures follow pre-existing weak planes in the nucleus being the result of a primordial, meter-scale nucleus heterogeneity. A crucially important question is if these goose-bumps exist at depth or exclusively as a surface phenomenon. CONSERT measurements of signal broadening because of volume scattering are consistent with structures with diameters up to 9 meters as long as the dielectric constant contrast between boulders and matrix is at most $\Delta\varepsilon \le 0.25$ (Ciarletti et al. 2017a). This is consistent with a boulder porosity of 60%, as predicted by Davidsson et al. (2016), as long as the surrounding material has a porosity of 95% (Ciarletti et al. 2017a).

Taken together, the properties of hierarchically grown comet nuclei (as predicted by direct numerical modeling of the process with codes accounting realistically for material behavior in the limits of high porosity and low collision velocity), as well as measured key properties of comet nuclei (such as the internal structure) are yet not known well enough to allow for a direct comparison. At this point it is not possible to prove or refute the hypothesis that comet nuclei grew through hierarchical agglomeration—however, the things we think we know about this process at least appear consistent with the things we think we know about comet nuclei.

3 Formation and Accretion of "Pebbles"

In this section we describe a formation model of planetesimals in which the protoplanetary dust grains first form mm- to cm-sized aggregates ("pebbles"), followed by pebble concentration and finally the gravitational collapse of the pebble cloud. Rosetta has delivered a wealth of new information about comet 67P, and we will utilize this information to test whether the gravitational-collapse model can describe its properties.

3.1 The Formation of Dust Aggregates

The physical processes that lead to the growth of aggregates from the initial (sub-) µm-sized dust and ice grains have been extensively described in the literature (Weidenschilling 1977; Dominik and Tielens 1997; Blum et al. 2000; Blum and Wurm 2008; Wada et al. 2008, 2009; Güttler et al. 2010; Schräpler et al. 2018). When dispersed in the gas of the protoplanetary disk, dust grains experience a variety of relative motions to the gas, e.g. Brownian motion, radial, azimuthal and vertical drift motions, or decoupling from turbulent eddies. Thus, the dust particles collide frequently.

If the binding energies of the dust particles experiencing a collision are strong enough, the kinetic collision energy can be dissipated and the particles stick together (Dominik and Tielens 1997; Wada et al. 2008, 2009; Güttler et al. 2010), thus forming loose aggregates. It has been shown numerically as well as experimentally that the initial stage of dust-aggregate growth is dominated by the formation of fractal aggregates (see Blum 2006 for details).

Due to the increasing collision energy with increasing dust-aggregate mass, collisional compaction occurs when the rolling threshold is overcome and results in the formation of non-fractal, but porous aggregates. For non-fractal dust aggregates collision speeds typically increase with increasing dust-aggregate mass, due to a size-dependent decoupling from the gas motion (Weidenschilling 1977). Numerical studies suggest that growth stops when the sticking threshold of the dust aggregates is reached, whereupon the particles are compacted in bouncing collisions (Weidling et al. 2009; Zsom et al. 2010; Lorek et al. 2018).

The growth timescale, τ_g, until the bouncing barrier is hit, is on the order of a few hundred to a few thousand orbital periods (Zsom et al. 2010; Lorek et al. 2018). The final aggregate size depends on the nebula model (Zsom et al. 2010) as well as on the monomer-grain properties (size, material), the heliocentric distance, the strength of turbulence and details of the collision physics, and typically falls into the 1 mm to 1 cm range (Lorek et al. 2018). These dust aggregates have been termed "pebbles".

Growth to larger sizes might be possible at the iceline or beyond as suggested by Ros and Johansen (2013). However, laboratory experiments suggest that any further growth well beyond pebble sizes is impeded by a variety of processes, among which the most prominent are bouncing, fragmentation and erosion. A recent study by Schräpler et al. (2018) has revealed that erosion alone limits the maximum achievable pebble size to $\sim$10 cm, even under the most favorable growth conditions.

Growth to pebble sizes has been observed in protoplanetary disks, with a tendency toward decreasing maximum pebble size with increasing distance from the central star. However, this result may be observationally incomplete for meter-sized bodies or larger, i.e., larger objects could not be detected by the observational techniques employed (see, e.g., van Boekel et al. 2004; D'Alessio et al. 2006; Natta et al. 2007; Birnstiel et al. 2010; Ricci et al. 2010; Pérez et al. 2012; Trotta et al. 2013; Testi et al. 2014; Pérez et al. 2015; Tazzari et al. 2016; Liu et al. 2017).

To describe the motion of dust particles (or pebbles) in the Solar Nebula, the Stokes number is the relevant property to consider. It describes, in dimensionless units, the efficiency of the frictional coupling of the dust particles to the gas motion. If the Stokes number is much smaller than unity, the dust almost perfectly follows the gas motion, whereas for very large Stokes numbers, the dust is decoupled from the gas and moves on Keplerian orbits. Formally, the Stokes number is given by: $St = \tau_f \Omega$, where τ_f and Ω are the gas-grain friction time and the orbital frequency, respectively. While the former depends on the dust-aggregate size and porosity as well as on the nebula-gas density, the latter is only a function of the heliocentric distance.

The Stokes number determines the drift motion of particles with respect to the gas. In particular, the radial drift motion limits the lifetime of the pebbles before they spiral into their central star. Typical drift timescales for $St \lesssim 1$ are $\tau_d = a/v_d \approx a/(2St v_{\max})$, where a, v_d and $v_{\max}$ are the heliocentric distance, the drift velocity, and the maximum deviation of the orbital gas velocity from the Keplerian speed (typically 50 m s^{-1}, see Weidenschilling 1977; Weissman 1990), respectively. The ratio of growth timescale to drift timescale becomes $\tau_g/\tau_d \approx 2 \ldots 20\, St$ for $a = 1$ AU and $\tau_g/\tau_d \approx 20 \ldots 200\, St$ for $a = 100$ AU. Thus, drift becomes important when the dust aggregates reach pebble sizes; see Lorek et al. 2018 for a detailed discussion on timescales. It is interesting to note that the pebble sizes at the transition from sticking to bouncing, as discussed above, are equivalent to Stokes numbers in the range: $St = 0.001 \ldots 1$.

3.2 Concentration of Dust Aggregates and the Gravitational Collapse of a Pebble Cloud

Once dust aggregates have reached pebble sizes, they partly decouple from the nebula gas, which can lead to their spatial concentration by, e.g., sedimentation to the disk midplane, inside or between turbulent eddies or in pressure bumps (see Johansen et al. 2014 for a detailed review of concentration mechanisms). If any one of these concentration mechanisms leads to a local dust-to-gas mass ratio greater than unity, the so-called streaming instability can further enhance the pebble concentration considerably on a few orbital timescales (Youdin and Goodman 2005).

The streaming instability works the following way: with increasing dust concentration, the pebble cloud is slowed down less and less by gas drag due to the decreasing surface-to-mass ratio of the collectively acting pebble ensemble. Once the dust concentration locally exceeds that of the gas, the pebble cloud moves with Keplerian velocity and not at the sub-Keplerian speed valid for isolated pebbles, which also greatly reduces its radial drift. In turn, the nebula gas inside and around the pebble cloud is dragged along with the pebbles and forced to move at Keplerian velocity. Thus, single pebbles or smaller pebble assemblies on the same orbit as the pebble cloud are overtaken and incorporated into the pebble cloud, increasing its mass. In addition, pebbles or pebble assemblies drifting radially inwards are also captured, adding their mass to the pebble cloud.

By this process, the pebble concentration is strongly enhanced until it reaches the gravitational-collapse limit. Johansen et al. (2007) showed that gravitationally bound planetesimals can form by this process. However, besides the required pre-concentration of pebbles, the streaming instability only reaches sufficiently high concentrations for a gravitational collapse if the metallicity is high enough and the Stokes numbers fall into the range $St \approx 10^{-3} \ldots 5$ (Yang et al. 2017). The minimum required metallicity is $Z \approx 0.015$ for $St \approx 0.1$ and $Z > 0.015$ for smaller or larger Stokes numbers. Thus, the "optimal" Stokes number occurs for $Z \approx 0.015$, which refers to pebble sizes on the order of $\sim$10 cm at 1 AU and $\sim$1 mm at 100 AU. Also, note that the solar metallicity is $Z \approx 0.0134$ (Asplund et al. 2009) and, thus, slightly smaller than the required minimum metallicity. To achieve a higher metallicity and thus to trigger the streaming instability, partial dissipation of the nebula gas might be required (see Davidsson et al. 2016 for a discussion).

The outcomes of a gravitational collapse triggered by the streaming instability have been extensively discussed in recent years. Wahlberg Jansson and Johansen (2014, 2017) and Wahlberg Jansson et al. (2017) describe the fate of the dust aggregates during the collapse. Following the fragmentation model of Bukhari Syed et al. (2017), Wahlberg Jansson et al. (2017) find that pebbles only survive the collapse intact for final planetesimal radii smaller than about 50 km. Thus, only smaller planetesimals consist of primordial dust aggregates. In a follow-up work, Wahlberg Jansson and Johansen (2017) found some size sorting during the collapse, which leads to an internal pebble-size stratification of the planetesimals.

With numerical resolution of the hydrodynamic models increasing over time, it has become evident that the planetesimals follow a differential power law mass-frequency distribution $\mathrm{d}N/\mathrm{d}M_p \propto M_p^{-x}$, with N and M_p being the number of planetesimals with mass M_p and a maximum planetesimal mass, $M_{p.max}$, corresponding to radii of $\sim 10^3$ km. The exponent is approximately $x = 1.6$ (Simon et al. 2016; Schäfer et al. 2017; Abod et al. 2018), which corresponds to a cumulative power-law size distribution exponent of -2.8. An even better fit to the data can be achieved for an exponentially truncated mass power law with an exponent, $x = 1.3$ (Abod et al. 2018), which corresponds to a cumulative size distribution exponent, $= -1.9$. As the current spatial resolution of the numerical models does not allow the formation of planetesimals with diameters $\lesssim$60 km, it is not known whether planetesimals of sizes comparable to cometary nuclei can form by the gentle gravitational collapse of pebble clouds.

The physical properties of planetesimals formed by the streaming instability with a final gravitational collapse have been analyzed by Skorov and Blum (2012), Blum et al. (2014), Blum et al. (2017) and Blum (2018). For planetesimal radii below $\sim$50 km, for which the pebbles should survive the collapse intact, the central lithostatic pressure is also not strong enough to structurally destroy the pebbles. Thus, we expect relatively homogeneous bodies (apart from the above-mentioned size-sorting effect) with two porosity size scales, i.e., on the length scale of the monomer grains (∼μm) and on the length scale of the pebbles (∼cm).

From experimental work, the packing fraction within the pebbles should be ∼0.4 (Weidling et al. 2009), following a period of bouncing collisions before their accretion into planetesimals. On the other hand, pebbles pack inside the planetesimal with a packing fraction of ∼0.6 (see Blum et al. 2017 for details) so that an overall porosity of $p \approx 1 - (0.4 \times 0.6) = 0.76$ should result. For larger planetesimals, for which the pebbles get destroyed during the collapse or by lithostatic compression, the inter-pebble void space should be absent, resulting in a porosity: $p \approx 1 - 0.4 = 0.60$. In terms of internal cohesion, the difference between small and large planetesimals is even more pronounced. While small planetesimals should have tensile strengths on the order of ∼1 Pa (Skorov and Blum 2012; Blum et al. 2014), large planetesimals should possess tensile strengths on the order of $\sim 10^3$ Pa (Blum 2018; Gundlach et al. 2018).

3.3 Comets as Test Cases for Planetesimal Formation Models

With extensive observational data, several cometary flybys and the vast quantity of Rosetta observations of comet 67P/Churyumov-Gerasimenko, we can now start to perform empirical tests of the above formation scenario. The most model-independent Rosetta measurements of 67P are those of the mass, $\sim 10^{13}$ kg, the volume, $\sim 2 \times 10^{10}$ m^3, and the bulk density, 533 kg m^{-3}, (Pätzold et al. 2016; Preusker et al. 2015). For the determination of the packing fraction or porosity, one needs to know the composition of the cometary matter (Levasseur-Regourd et al. 2018), which is controversially debated, in particular the dust-to-ice mass ratio (Fulle et al. 2019). Due to its large sampled volume, the best material constraint at this time comes from the Rosetta CONSERT instrument, which arrived at a dust-to-ice mass ratio of 3–5 and a porosity, $p > 0.65$, most likely around $p \approx 0.75$ (Herique et al. 2016), in good agreement with a pebble-collapse model and a small planetesimal size (see above).

Blum et al. (2017) performed an analysis of whether comet 67P consists of pebbles, based on five different sets of Rosetta instrument data: (1) They modeled the thermophysical behavior of the near-surface layers with a pebble model, determined the subsurface temperature stratification and the resulting thermal radiation fluxes at the two Rosetta MIRO wavelengths, 0.5 and 1.6 mm. For reasonable optical properties of the cometary matter in the mm wavelength regime, Blum et al. (2017) could reproduce the Rosetta MIRO fluxes for pebble radii between 1 and 7 mm. (2) Similarly, the surface temperatures measured by Philae MUPUS-TM could be modeled with pebble radii between 0.2 and 55 mm. (3) From an analysis of the size-frequency distributions measured by various Rosetta instruments and from the ground, Blum et al. (2017) derived that most of the ejected dust mass was in particles with radii between 1 and 10^3 mm. (4) With the published tensile strength data for 67P (Groussin et al. 2015; Thomas et al. 2015; Hirabayashi et al. 2016), Blum et al. (2017) arrived at pebble radii of up to 6 mm using the model of Skorov and Blum (2012) and measurements by Blum et al. (2014) and Brisset et al. (2016). However, newer results from Attree et al. (2018) suggest tensile strengths of <1 Pa on the pebble size scale, which can be achieved with pebble radii larger than ∼1 mm. Low strength values close to the surface of a comet nucleus are supported by impact-crater modeling by Housen and Holsapple (2007) who predicted the observed crater size (150 m diameter) of the Deep Impact mission on comet Tempel 1 for a tensile-strengths of ∼1 Pa. (5) Finally, images taken with the Philae/CIVA camera at the final Philae landing site with a spatial resolution better than 1 mm, showed a rugged terrain in which Poulet et al. (2016) identified 695 pebbles. The cumulative size-frequency distribution of these pebbles, as seen in Fig. 6 of Poulet et al. (2016), shows a clear mass peak at pebble radii between 3.5 and 6 mm. Interestingly, this corresponds to Stokes numbers, $St \approx 0.1$ at 30 AU with a minimum-mass solar-nebula model, which is the minimum required metallicity for the streaming instability to occur (see above).

A comet nucleus made of pebbles can also explain the sublimation-driven dust activity, particularly if the pebbles have sizes on the order of $\sim$1 cm. Only then is the sublimation pressure below the desiccated dust-aggregate layer strong enough to lift the pebbles off the surface (Skorov and Blum 2012; Blum et al. 2014, 2015; Gundlach et al. 2015; Bischoff et al. 2019). Also, the steeply increasing sublimation rate of water ice with decreasing heliocentric distance can be explained by the pebble model of comet 67P (Blum et al. 2017; Hu et al. 2019).

Moreover, the inactivity of asteroids in comet-like orbits (ACOs) can be explained by the pebble model, as Gundlach and Blum (2016) have shown. Although the orbital parameters of ACOs are almost indistinguishable from JFCs (Kim et al. 2014), ACOs do not generally show dust activity. Gundlach and Blum (2016) explain this by the larger sizes of the ACOs compared to the JFCs. While JFCs and ACOs possess a very similar size-frequency distribution for radii between 1 and 2 km, there is an excess of ACOs at larger sizes. Due to the larger size and the correspondingly larger lithostatic pressure inside the ACOs and a memory effect described by Blum et al. (2014) and Gundlach and Blum (2016), the sub-surface tensile strength of ACOs is higher than that of JFCs. Bodies become inactive whenever the tensile strength can no longer be overcome by the internal gas pressure of the sublimating volatiles. As a result, the depth at which inactivity happens is shallower for larger bodies (i.e., for ACOs) than for the smaller JFCs. Thus, assuming a constant depth of erosion per orbit (as suggested by the similar orbital parameters), JFCs can turn into ACOs after a finite number of orbits, which is smaller for large bodies than for small ones.

Also observation of very large dust particles with masses up to 100 kg in the coma of comet 67P (Ott et al. 2017) can be explained by the pebble model. Blum et al. (2017) speculated that most of the dust mass loss in the southern hemisphere of 67P is emitted in particles between 1 and 10^3 mm in size, and that these particles are either single pebbles or clusters of pebbles. In a recent study, Bischoff et al. (2019) showed that the lateral size of an emitted dust patch slightly exceeds its depth so that one can expect that the chunks are clusters of pebbles with similar dimensions in all directions. Gundlach et al. (personal communication) showed that chunks with sizes exceeding 10 cm in depth can be emitted during the southern hemisphere summer owing to the sublimation of CO_2 ice.

The reported measurement of extremely fluffy dust particles by Rosetta GIADA (Fulle et al. 2015) with porosities $p \gtrsim 0.99$ and the discovery of a fractal dust aggregate by Rosetta MIDAS (Mannel et al. 2016) were explained by Fulle and Blum (2017). In their model, these high-porosity or fractal particles are primordial aggregates from the early stages of dust growth, which coexisted with the pebbles and were stored safely away inside the inter-pebble pores as the nucleus of comet 67P formed by the gentle gravitational collapse of a pebble cloud.

To summarize, there is strong evidence for an abundance of mm- to cm-sized particles in 67P, which might be identified as the pebbles grown in the Solar Nebula. The observed bulk density and tensile strength of 67P appear consistent with a gentle collapse of a pebble cloud. However, further modeling is needed to demonstrate that kilometer-sized bodies do form by this mechanism, that the properties of comets are unique to this mode of formation, and that they are not ruined by high-velocity collisional evolution, should that have taken place. Also the existence of extremely fluffy grains is not in line with the hierarchical growth model. However, the dominance of pebbles in cometary observations is far from being the final proof for the formation of planetesimals by the streaming instability. For instance, there exists the possibility that follow-up collisional processes (see Sect. 4) might have turned the planetesimals into rubble-pile bodies with typical size scales of mm to cm. This needs to be investigated in the future before the uniqueness of one or the other formation model for cometary nuclei can be confirmed.

4 Collisional Evolution of Comets

The comets that we see today as ecliptic or nearly-isotropic comets (see Levison and Duncan 1997 for definitions) come from the Scattered disk and the Oort cloud, respectively. But, before joining these low-density reservoirs, the comets remained for some time in their original orbits, i.e., the massive trans-Neptunian planetesimal disk, earlier referred to as the Primordial Disk. According to the most accurate models of solar system dynamical evolution (Nesvorný and Morbidelli 2012; Nesvorný 2015a, 2015b; Nesvorný and Vokrouhlický 2016; Nesvorný et al. 2017) this planetesimal disk was located between an inner edge at ∼15–20 AU and an outer edge at ∼30–40 AU and comprised 20 to 30 Earth masses of material. The dispersal of this disk during a phase of instability of the giant planets generated the hot population of the Kuiper belt (Nesvorný 2015a), the Scattered disk and the Oort cloud (Brasser and Morbidelli 2013; Nesvorný et al. 2017), the Trojan populations of Jupiter and Neptune (Nesvorný et al. 2013; Nesvorný and Vokrouhlický 2009) and the clouds of irregular satellites of the giant planets (Nesvorný et al. 2007). The size distribution of the disk at the time it was dispersed, deduced by combining a series of observational constraints from these daughter populations, was presented in Nesvorný and Vokrouhlický (2016) and is depicted in Fig. 1.

This size distribution is similar to that of the current Kuiper belt deduced in Robbins et al. (2017) in the 200 m–10 km range from the crater size-frequency distributions on Pluto and Charon, if one assumes that a crater on these bodies is roughly 10× the size of the projectile that caused it, as estimated from crater impact models (Melosh 1989). In particular the turnover of the cumulative impactor size distribution from one steeper than $q = -2$ for $D > 1.5$ km to one shallower than $q = -2$ for $D < 1.5$ km seems to be a recurrent feature on most imaged terrains.

A question arises because the cumulative slope of −3 found for KBOs with $1 < D < 10$ km in Fig. 1 (left) is steeper than any slope derived from direct observations of JFCs, whose cumulative slopes range from −1.9 to −2.7 (Snodgrass et al. 2011; Belton 2014; Tancredi et al. 2006; Meech et al. 2004). This issue was recognized by Nesvorný and Vokrouhlický (2016). They suggested that it may be due to the surface mass loss of JFCs after they leave the Kuiper belt. Still, it is an open question that needs to be resolved.

At diameters, $D \leq 100$ km, the distribution in Nesvorný and Vokrouhlický (2016) is similar to that measured in the asteroid belt, which is the result of a collisional evolution that has reached equilibrium (Bottke et al. 2005). Unless coincidental, this suggests that the trans-Neptunian planetesimal disk had time to evolve to collisional equilibrium before being dispersed. If this is the case, comet-size objects (typically a few km in diameter) should have experienced many collisions. Presumably, most of those we see today should be fragments of originally larger objects.

Reasoning by the absurd, Morbidelli and Rickman (2015) assumed that the size-frequency distribution in the planetesimal disk is primordial (i.e., was determined by the

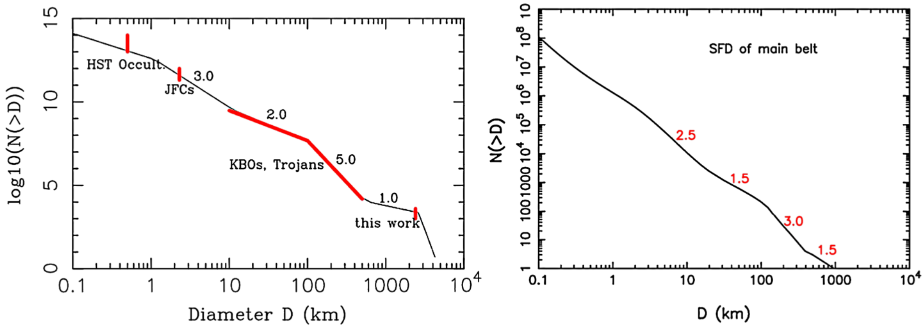

Fig. 1 Left panel: The cumulative size distribution in the trans-Neptunian disk at the time it was dispersed, according to Nesvorný and Vokrouhlický (2016). The numbers indicate the local slopes of the distribution. Note that the numbers for the local slope values should be negative numbers, the number of objects decreasing with increasing size. The main constraints used for this reconstruction are also indicated. Right panel: The cumulative size distribution in the main asteroid belt, from Bottke et al. (2005). Numbers again indicate local slopes and should be taken as negative numbers

accretion process, not by collisional evolution) and computed the probability that a cometesimal with $D = 4$ km is collisionally disrupted. If the resulting probability is high, clearly the assumption is invalid. The size-frequency distribution assumed by Morbidelli and Rickman was very similar to that found in Nesvorný and Vokrouhlický (2016), comprising 2×10^{11} bodies with $D > 2.3$ km, with a slope of -2 in the cumulative size distribution at less than 2.3 km. Morbidelli and Rickman found that, if the planetesimal disk remained massive for $\sim$50 Myr or more before being dispersed by the giant planets instability, the probability that a $D = 4$ km body is disrupted by a catastrophic collision exceeds 1. That is, all the original planetesimals at this size should have been disrupted and therefore those existing today would be fragments of larger bodies. Only in the case where the disk was dispersed immediately after planetesimal formation would comet-size planetesimals have had a chance (nevertheless smaller than 50%; Jutzi et al. 2017) to avoid catastrophic disruptions.

Focusing on this last possibility, Jutzi et al. (2017) computed the probability that a comet nucleus like 67P preserved its shape. Preserving the bilobate shape is less probable than avoiding all catastrophic collisions, because the collisional energy sufficient at smashing one of the lobes is about two orders of magnitude less than the catastrophic disruption energy for the comet nucleus as a whole (Jutzi et al., Fig. 7). Assuming a size distribution like that in Morbidelli and Rickman (2015), Jutzi et al. concluded that during disk dispersal a 67P-like object would have suffered 10–50 reshaping collisions, concluding that the morphology of the comet that we observe today cannot be primordial.

These results raise a number of interesting questions: First, if the bilobate shape of 67P is not primordial, how was it acquired? Notice also that bilobate shapes are common for JFC nuclei, so one cannot invoke any “singular” argument to explain the shape of 67P. Jutzi and Benz (2017) showed that the shape could have been acquired in a sub-catastrophic collision of a somewhat larger progenitor. A collection of bilobate shapes obtained in Jutzi and Benz sub-catastrophic collisions is shown in Fig. 2.

Schwartz et al. (2018) showed that the bilobate structure can be obtained also in catastrophic collisions, although the bilobate shapes they could generate are less pronounced than in Jutzi and Benz (2017). This is not necessarily a problem because the lower is the collisional energy the higher is the probability for it to happen (because a smaller projectile is required) so the last relevant collision that 67P suffered was most likely a sub-catastrophic one.

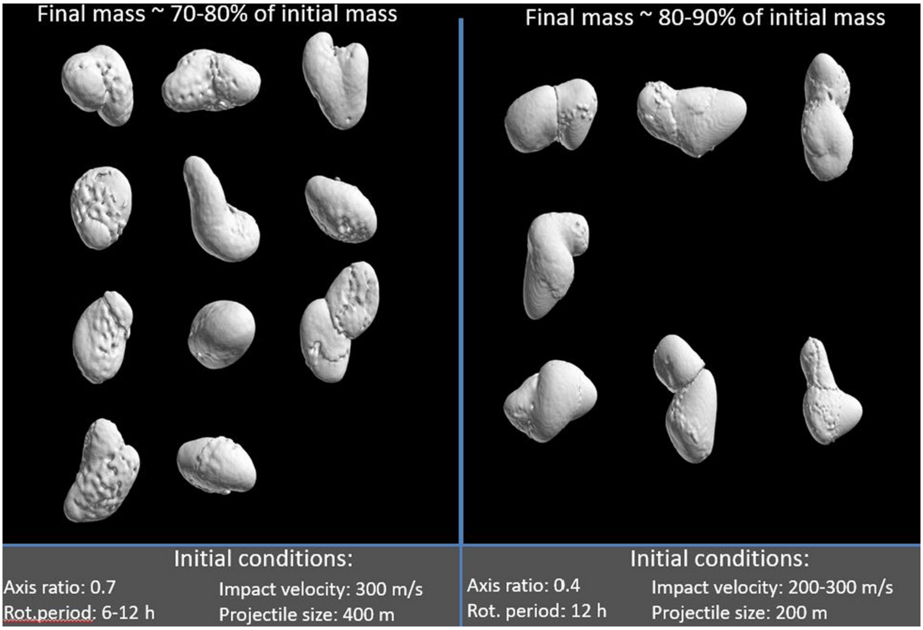

Fig. 2 Examples of bilobate shapes obtained in the SPH sub-catastrophic collision experiments of Jutzi and Benz (2017)

A second important question is whether catastrophic fragmentation would lead to compaction and heating. If this were the case, the high porosity and low-temperature chemistry observed for 67P and other comets would become strong constraints against comets being fragments of significantly larger objects. Schwartz et al. (2018) showed that only a tiny fraction of a comet would have been heated by more than few degrees by the catastrophic collision that generated it. A larger fraction of the parent body might have been substantially heated, but the heated material is typically not incorporated in macroscopic fragments; see Fig. 3.

An analogous result was found for the porosity. It should be noted, however, that the collisions in Schwartz et al. (2018) are just above the catastrophic limit and the parent bodies considered are quite small: about 7 km in diameter. The streaming instability simulations show that the most typical planetesimal produced in the accretion process should have had $D = 50$–100 km. Catastrophic collisions of parent bodies of these sizes have not yet been simulated, so we don't know whether the same results concerning heating and compaction apply. Simulations of this kind can provide constraints on how large the progenitors of the collisional cascade leading to comet-sized objects could be. The specific energy in catastrophic collisions for bodies with $D = 16$, 32, and 64 km are 3, 7.2, and 17 $\mathrm{kJ\,kg^{-1}}$, respectively. If distributed uniformly these energies would correspond to global temperature enhancements of 12, 29 and 69 K. At 69 K, CO_2 would sublimate throughout the warm interior and recondense at the rapidly cooling surface, releasing the CO trapped in the cages of the original CO_2 ice (Gasc et al. 2017). CO would therefore escape into space, leading to CO-depleted fragments. However, 67P/CG and most comets are rich in CO. Therefore this argument suggests that they cannot be fragments of progenitors with $D = 20$ km or larger. Thus, it is essential to quantify how uniform the temperature increase would be in the pro-

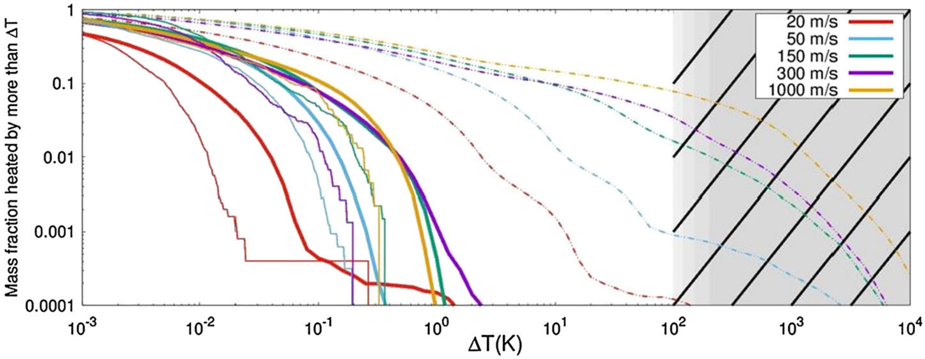

Fig. 3 Solid curves show the fraction of the mass of the resulting comet that has been heated above a given temperature in a catastrophic collision of a larger parent body. Different colors relate to different impact speeds, the projectile being smaller at higher speed. The dashed curves show the same fraction for the parent body material. At high speed (1 km/s), 20% of the parent body can be heated by more than 10 degrees, but none of the over-heated material is incorporated in the largest remnant. From Schwartz et al. (2018)

genitor and the peak temperatures in the main fragments in simulations like that of Schwartz et al. (2018) applied to larger-scale collisions.

A third relevant question is whether the original pebbles, potentially detected in 67P (see Sect. 3), would be preserved in a catastrophic collision, or if re-accumulated collisional fragments have sizes less than a few meters as constrained by CONSERT. The SPH simulations of Schwartz et al. do not have the resolution to address these questions and there is still a long way to go before this can be done.

5 Comet Nucleus Evolution

As noted in the Introduction, comet nuclei are among the most primitive bodies in the solar system. Because of their small size and storage in two cold, distant reservoirs they have likely experienced the least physical processing of any known solar system bodies. Yet it has long been recognized that nuclei do evolve and change with time. The Rosetta mission provided absolute proof that 67P was a body undergoing “active” geological processes, in particular mass-wasting and fracturing, that have modified the nucleus surface and possibly the interior (Thomas et al. 2015).

“Primitive” is a relative term and it is important to define what we mean by that. Precursor elements and molecules that were incorporated in comets were processed in the interstellar medium and before that in the cores of massive stars, possibly multiple times. Volatile ices are deposited onto interstellar grains where UV radiation and cosmic rays provide chemical evolution. Further processing occurs as the natal interstellar cloud collapses and material is brought together in denser and warmer environments.

For the purposes of this paper we will define “primitive” as the chemical state of cometary materials as they began to agglomerate/accrete into macroscopic bodies. As the surfaces of these bodies are modified by the physical processes described below they lose their primitive nature, but the nucleus interior likely remains primitive. Given the earlier processes mentioned above, it would be wrong to ever refer to these bodies as “pristine” as some researchers mistakenly do.

As noted in Sect. 4, the initial processing of comet nuclei was accomplished by collisional evolution in the planetesimal disk and subsequently as the giant planets cleared their zones of remaining planetesimals. The current Nice Model (named for the Observatoire de Nice where the initial work was done; Tsiganis et al. 2005; Gomes et al. 2005) for the solar system's early evolution suggests that this could have occurred very violently if Jupiter and Saturn passed through a mean-motion resonance. According to the Nice Model a relatively compact giant planets region was pushed outward due to planetary migration and huge swarms of icy planetesimals were dispersed to orbits in the Kuiper belt region or to the distant Oort cloud. Simulations of these processes by Stern and Weissman (2001) and Charnoz and Morbidelli (2003, 2007) suggested that under some starting conditions, comet nuclei might have ground themselves to dust during this dispersal, though this result is very dependent on what was assumed for the typical size of a comet nucleus as well as the number of comets in the Disk.

5.1 Processing in the Kuiper Belt and Oort Cloud

Although we think of the Kuiper belt and Oort cloud as very benign environments, there are processes that would have modified the comet nuclei there. These include: (1) internal heating by short-lived radio-nuclides, (2) irradiation by galactic cosmic rays and solar protons, (3) heating by stars passing through the Oort cloud and by nearby supernovae, (4) accretion of interstellar molecules and dust grains, (5) erosion by hyper-velocity interstellar dust grain impacts.

(1) Even as they are first accreting in the Primordial Disk, comet nuclei are warmed by short-lived radio-nuclides, in particular ^{26}Al. Prialnik et al. (1987) showed that the central temperature of cometary nuclei with radii of 1, 5, and 10 km would be heated to 15, 60 and 90 K respectively in 10^6 to 10^7 years. This was for nuclei composed solely of amorphous water ice, contaminated with several of the expected short-lived radioactive isotopes in their solar system abundances. None of these temperature values are high enough to convert the amorphous water ice into crystalline water ice. These central temperatures would be even lower if we consider the nuclei to be an even (1:1) mixture of amorphous water ice and meteoritic non-volatiles since the non-volatiles would absorb some of the heat from the radio-nuclides. Some of the most volatile ices would sublimate at the temperatures above and then would diffuse through the porous nucleus until they reached colder layers where they could recondense. Note that these modeling results are sensitive to the size of the nuclei, their porosity, and the initial ^{26}Al content (Prialnik and Podolak 1995, 1999). The Prialnik and Podolak models use an ^{26}Al initial mass fraction of 5×10^{-8} of the non-volatile mass, which is somewhat lower than the value found from studies of primitive meteorites.

Giotto measurements (McDonnell et al. 1989) suggested that the dust-to-ice mass ratio in the 1P/Halley coma was $\sim$2:1. Rosetta measurements (Rotundi et al. 2015; Herique et al. 2016) were even higher, with the mass of non-volatile dust in 67P being 3–5 times the mass of the sublimating ices, even when such ices as CO and CO_2 were included. This creates a new problem because the mass fraction of ^{26}Al and other short-lived radio-nuclides would provide a larger internal heat source. Future modeling of the internal temperatures of comet nuclei will need to take this into account.

(2) Irradiation of volatile ices and ice-dust mixtures by high-energy particles has been studied in the laboratory (Johnson 1991; Cooper et al. 1998; Strazzulla 1999). The interaction breaks chemical bonds producing volatile free radicals, some of which recombine to form a dense, dark polymer which is far less volatile than the original material. Polymerization occurs particularly if hydrocarbons are present, which we know to be the case for

cometary nuclei. At the nucleus surface, the high energy particle bombardment results in a net erosion by sputtering (observed at 67P by the ROSINA instrument on Rosetta; Wurz et al. 2015) and probable escape of the more volatile species, leaving behind a low-volatility residue.

The depth to which the particles penetrate the nucleus surface depends strongly on the energy of the particles and the bulk density of the surface layers. Low-energy solar protons of a few to a few hundred keV penetrate only the top millimeter; cosmic ray protons with typical energies of 2 MeV penetrate 1–2 meters. This raises the interesting possibility that comets from the Kuiper belt and Oort cloud may have already developed thick non-volatile crusts before they are perturbed to smaller and warmer perihelion distances.

(3) Random passing stars occasionally penetrate the Oort cloud, heating the comets along their path and ejecting them to interstellar space. For solar mass stars, comets out to about 500 AU from the star's path will be dynamically ejected. This is much greater than the distances at which significant heating occurs, so all the heated comets will be lost. But for very massive and luminous OB giants, the heating radius is larger than the ejection radius. Stern (1987) estimated that all comets in the Oort cloud have been heated to 27 K and that 20% to 40% had at least one episode of heating to 50 K. These warming events occur over periods of several thousand years and thus should be sufficient to warm most of each nucleus to these temperatures. As a result the more volatile ices will have been mobilized within the nucleus and some fraction can be expected to be lost from near-surface layers.

Such heating events in the Kuiper belt will be far less frequent because of its smaller cross-section relative to random passing stars. Whereas the Oort cloud has a radius of $\sim 10^5$ AU or more, the (known) Kuiper belt extends only about 50–100 AU. The Scattered disk, the source of the JFCs, extends $\sim 10^3$ AU so it too is relatively unlikely to have experienced significant external heating.

(4) and (5) The competing processes of erosion by hypervelocity interstellar dust impacts and accretion of interstellar gas and dust grains only affect a very thin layer at the nucleus surface. Stern (1986) estimated that micro-cratering by grain impacts will remove a layer only 5–80 mm in thickness over a comet's lifetime in the Oort cloud. O'Dell (1971) estimated that accretion of interstellar gas and dust would add a layer only 10–100 microns in thickness to a nucleus surface. Although dust gains can be captured in impacts with very low density media such as the aerogel used on the Stardust mission (Tsou et al. 1984) the much higher bulk density of 67P would result in grain impacts being erosional rather than accretionary.

5.2 Solar Heating

The major processing of comet nuclei occurs when they are perturbed back into the planetary region and are subject to the heat of the Sun. Weissman (1979) and Fernández (1981) showed that the typical long-period comet (LPC) from the Oort cloud makes only 5–11 returns before it is dynamically ejected or randomly disrupted (though some comets may survive for tens or even hundreds of returns). Thus the physical evolution of these LPCs is probably not very significant during their relatively short dynamical and disruption lifetimes in the planetary region.

For Jupiter-family comets like 67P, also known as "ecliptic comets," their history can be much more complex. Comets in the Kuiper belt and the Scattered disk can make close approaches to Neptune and be perturbed to orbits with smaller perihelia. Neptune can gravitationally scatter these comets to Uranus which will then pass them on to Saturn, and eventually Jupiter.

Levison and Duncan (1997) studied this dynamical process using Monte Carlo codes. They found that a typical Kuiper belt or Scattered disk comet took 4.5×10^7 years to reach one of two possible end-states: dynamical ejection from the solar system or striking a planet. Thirty percent of these comets became Jupiter-crossing with perihelia ≤ 2.5 AU, where Levison and Duncan defined them to be "visible comets." By comparing the predicted orbital element distributions from their simulations to that of known JFCs, they estimated that the typical JFC spent 1.2×10^4 years as a visible comet. If we take a typical JFC orbital period of 6 years, this suggests the lifetime of ecliptic comets in the active region ($q < 2.5$ AU) is $\sim 2 \times 10^3$ returns.

These planet-crossing orbits are not very stable and can change on time scales of a few to tens of orbits. As the most massive planet, Jupiter dominates the motion of the JFCs. Close approaches to Jupiter will random walk perihelion distances closer to and farther from the Sun, as well as changing the orbital periods and inclinations.

For example, 67P itself was discovered in 1969. Integration of its orbit backward in time indicated that the comet made a close approach to Jupiter, $d = 0.052$ AU, in February 1959. That encounter reduced its perihelion distance from 2.74 AU to 1.28 AU (Kronk 1984; Krolikówska 2003). Around the year 2200 67P will make another close approach to Jupiter that will likely raise the perihelion distance back to $\sim$2.6 AU. Because of nongravitational forces caused by jetting of volatiles from the nucleus surface, no JFC can have its past or future orbit reliably predicted past one or two of these close Jupiter approaches.

The activity of 67P during the Rosetta mission is documented in detail in many of the other papers in this volume and will only be summarized herein. One of the main results from Rosetta is the variety of geological processes that were observed on the nucleus. These included airfall, thermal fracturing, surface dust transport, mass wasting, insolation weathering, orbiting debris and mass loss through the ejection of large chunks of material (Thomas et al. 2015). Much of the activity of the nucleus appears to come from vertical cliffs that were observed to crumble over time (Vincent et al. 2016a), exposing the volatile rich interior. This result was also suggested to explain the mesa-like structures observed on the nucleus of comet 19P/Borrelly during the Deep Space 1 flyby (Soderblom et al. 2002), and possibly on comet 9P/Tempel 1 (Veverka et al. 2013).

Another major result from Rosetta is that seasonal effects on 67P were particularly strong with important consequences (Keller et al. 2015). Because of the eccentricity of 67P's orbit, $e = 0.64$, and the obliquity and orientation of its rotation pole, most of its orbital period is spent with the Sun over the northern hemisphere. However, close to perihelion the Sun moves quickly to southern latitudes that have not seen any sunlight for the previous $\sim$6 years. This leads to a sharp rise in activity that lasts only $\sim$6–9 months before the Sun once again moves to northern latitudes.

This extreme seasonal behavior was proposed by Weissman (1987) who was trying to explain the post-perihelion brightening of Halley's Comet. The southern "nuclear summer" that 67P experienced in mid- to late-2015 led to significant differences between the two hemispheres. The southern hemisphere outgassing close to perihelion produced huge quantities of dust, much of which fell back onto the relatively inactive northern hemisphere, while preventing significant dust deposition on the southern hemisphere. It is noted that, like 1P/Halley, 67P reaches maximum activity and brightness post-perihelion. When the Sun is over the northern hemisphere, 67P is farther from the Sun and thus the activity is not high enough to remove the dust coatings obtained during southern hemisphere summer. This situation has likely repeated itself every perihelion passage since 67P was perturbed to its current orbit circa 1960.

A very important Rosetta result for our purposes comes from the Radio Science Investigation, which measured the mass of the 67P nucleus before and after perihelion (Pätzold et al. 2016, 2017). It was found that the comet lost $\sim 0.1\% \pm 0.03\%$ of its mass during the perihelion passage. First-order thermal models suggest that the average decrease in radius of a JFC on each orbit is a constant, i.e., the thickness of the removed layer is the same from orbit to orbit. This in turn suggests that 67P has a remaining physical lifetime of $\sim 10^3$ returns, if the current orbit and activity level were to remain unchanged. As noted above, the orbit will vary considerably. Interestingly, this is, to first order, similar to the 2×10^3 returns found by Levison and Duncan (1997) for the JFC population as a whole.

If we assume that the mass loss from the nucleus is uniform over the measured surface area of 51.7 km^2 (Preusker et al. 2017) and we assume the nucleus bulk density = 533 $kg\,m^{-3}$ (Pätzold et al. 2016, 2017) then the mean thickness of the removed layer is ~ 3.3 m ($\pm 30\%$). Note that more material is lofted off the nucleus surface but some fraction of it falls back, in particular onto the northern hemisphere, which is not illuminated around perihelion.

Another interesting Rosetta result is that the rotation period of the nucleus changed from one orbit to the next. Lowry et al. (2012) determined a rotation period of 12.76 hours for 67P from ground-based observations during the 2006 aphelion passage. However, at spacecraft rendezvous in 2014, the Rosetta OSIRIS (Imaging) Team found a period of only 12.41 hours (Sierks et al. 2015), a difference of approximately 21 minutes. Following 67P's perihelion passage and return to larger solar distances in 2015–2016, the rotation period decreased further to 12.07 hours, another change of ~ 20 minutes (Gaskell et al. 2016).

This behavior was seen previously for comet 9P/Tempel 1 (Chesley et al. 2013). It is caused by outgassing torques from the irregularly shaped nucleus, as well as the differences in seasonal outgassing rates. It is essentially the same nongravitational forces that change the comet's orbital parameters, in particular the orbital period.

Comet 67P also exhibited outbursts close to the time of perihelion on an almost daily basis (Vincent et al. 2016b). These outbursts tended to be located close to the sub-solar latitude at the time. The cause of the outbursts is still under investigation. One possibility is the sudden escape of volatile gases from a sealed sub-surface cavity. Another is the transition of amorphous water ice to crystalline water ice at depth, which is an exothermic reaction that occurs at temperatures between 110 and 150 K. A third possibility is that dust and gas are suddenly released when a vertical cliff collapses and exposes fresh cometary volatiles.

5.3 Sub-Surface Heating

Sunlight falling on the surface of a cometary nucleus is divided between three uses. Because of the low albedos of nucleus surfaces, ~ 3–7% (Lamy et al. 2004) only a small fraction is reflected back into space. The rest of the energy flows into the nucleus surface where it is divided between heating the cometary materials and the sublimation of cometary ices. As stated above, a result of this heating is that amorphous water ice will convert to crystalline water ice, which is an irreversible process.

Sublimation rates are highly dependent on the local temperature; they are a direct function of the vapor pressure of gas molecules over their respective ices, which vary exponentially with temperature (e.g., Lide 2004). The conversion rate of amorphous ice to crystalline ice is also highly temperature dependent.

The "thermal skin depth" is a measure of how far surface heat will penetrate below the surface (Rickman 1991). It is defined as:

$$d = (KP/\pi\rho C)^{1/2} \tag{5.1}$$

where K is the thermal conductivity, P is the period (rotation period for diurnal skin depth, orbital period for orbital skin depth), ρ is the density, and C is the specific heat. The thermal skin depth is the distance over which a temperature perturbation at the surface will decrease by a factor of 1/e. For conductivities typical of solid water ice, $d = 20$ cm for a rotation period of 24 hours or 9.2 meters for an orbital period of 6 years. However, for the low conductivities actually measured for nucleus surfaces, the diurnal skin depth is $\sim$1 cm while the orbital skin depth is about 1 meter.

As the thermal wave penetrates beneath the nucleus surface it will sublimate and mobilize ices. For ices more volatile than water ice, this occurs at substantially lower temperatures and greater depths than for water ice. The result is that volatile ices will be mobilized at depths where water ice is still relatively stable. Because of the low bulk density and high porosity of the nuclei the evolved gases can diffuse both upward toward the surface and inward to greater (cooler) depths where they will recondense (Espinasse et al. 1991). This will make for a complex composition in the near-surface layers of the nucleus.

Rosetta showed that the actual effects of sunlight on the nucleus surface were far more complex than can be described herein. As noted above, we leave those discussions of active geology to the other papers in this volume that specifically address them.

6 Nucleus End-States

There are a variety of possible end-states for cometary nuclei, several which have actually been observed. The end-states we identify are:

1. Random disintegration/disruption.
2. Tidal disruption.
3. Loss/burial of all volatiles leading to an asteroidal-appearing object.
4. Collision with the Sun, a planet or a satellite.

6.1 Random Disintegration/Disruption

Comet nuclei are often seen to spontaneously disrupt (Weissman 1980; Boehnhardt 2004). For example, comet C/1999 S4 LINEAR was seen to break into at least 16 pieces as it approached perihelion in July 2000 at a heliocentric distance of $\sim$0.76 AU (Weaver et al. 2001; Fig. 4). All trace of the comet disappeared within about three weeks.

The reasons for random disruption are not known but a leading candidate is rotational spin-up due to asymmetric outgassing torques from the irregular nucleus. Weissman and Lowry (2008) showed that no comet nucleus with a measured rotation period spins faster than about 5.5 hours. If comet nuclei are strengthless rubble piles held together only by self-gravity, this sets an upper limit on the nucleus bulk density of $\sim$600 kg m^{-3}. The Radio Science Investigation and the OSIRIS imaging team on Rosetta determined a bulk density for the 67P nucleus of 533 ± 6 kg m^{-3} (Preusker et al. 2015; Pätzold et al. 2016).

Random disruption does not appear to be correlated with any known orbital parameters such as perihelion distance, orbital inclination, pre-/post-perihelion time, etc., suggesting that it is some internal property(s) of the nucleus that leads to this loss state. Another suggested mechanism for random disruption is thermal stresses due to the strong thermal gradients as cometary surface materials rotate in and out of sunlight. Rosetta images of the 67P nucleus show considerable evidence of thermal stressing and cracking (Auger et al. 2018). This included cracking on the walls of the cylindrical pits that extend 100 m or more below the 67P nucleus surface (Vincent et al. 2015).

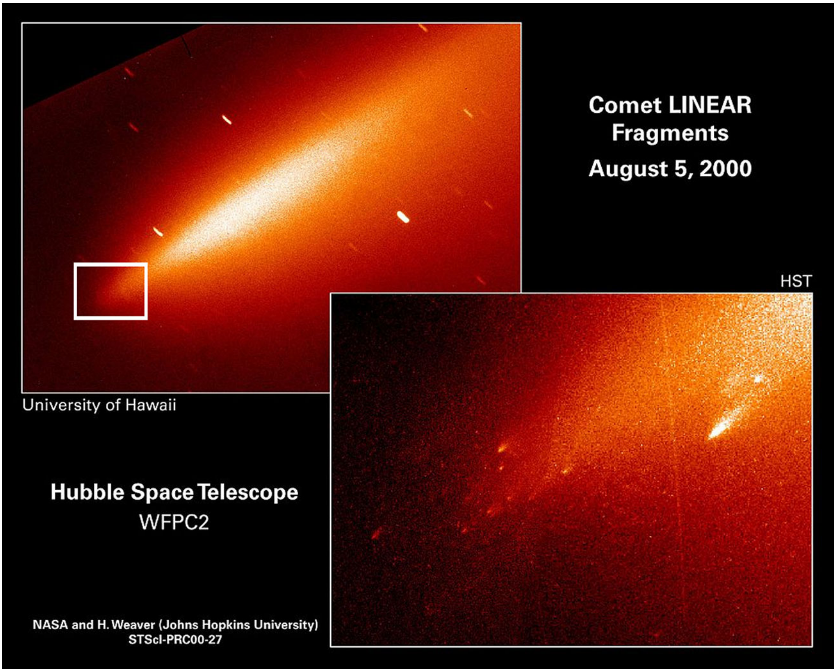

Fig. 4 Images of the disintegrating comet C/1999 S4 from a ground-based telescope (upper left) and from the Hubble Space Telescope (lower right). The approximate field of view of the HST image is shown by the small white box on the upper left image. Many individual fragments of the comet are seen in the HST image

Lastly, the development of sealed pockets of volatile gases below the nucleus surface may have some effect on splitting. Rosetta observed many outbursts around perihelion and the outbursts clustered along the sub-solar latitudes (Lin et al. 2017). A problem with this scenario is how do sealed pockets form in such a porous medium as the cometary nucleus?

Random disruption may not always lead to complete destruction of the nucleus. Comet 73P/Schwassmann-Wachmann 3 was observed to break into four separate nuclei at its perihelion passage in 1995 (Boehnhardt et al. 1996). For identification purposes these fragments were labeled A, B, C and D. All four fragments returned in 2006. Observations with HST showed that the fragments were individually shedding many smaller pieces on the order of 50 m or less in diameter (Weaver et al. 2006, see Fig. 5).

Another interesting case is periodic comet 3D/Biela which was first discovered in 1772 and observed on several returns (Kronk 1984). During the 1846 return it was found to be a double, comet with two independent nuclei that slowly moved apart. The double-comet was observed again in 1852. Observing conditions were unfavorable in 1859 but were good in 1865. However neither comet was recovered. The comets were not found at their predicted return in 1872 but an unexpected and intense meteor shower, ∼3,000 meteors per hour, was observed that year consistent with particles in the comets' orbits. Additional intense meteor showers were observed at the comets' predicted returns in 1885 (15,000 meteors per hour) and 1892 (6,000 meteors per hour), and a smaller shower in 1899 (150 meteors per hour). Neither the comets nor the meteor showers were found on subsequent returns.

Yet another possible example of a surviving split comet pair may be periodic comets 42P/Neujmin 3 and 53P/Van Biesbroeck. Integration of the comets' orbits backward in time show them to be remarkably similar prior to a close Jupiter encounter in 1850 (Carusi et al.

Fig. 5 HST images of the disintegrating B-fragment of comet Schwassmann-Wachmann 3 in 2006. The numerous small fragments breaking off of the B-fragment are readily seen and can even be traced from day to day. An upper limit of 50 m each was determined for the size of the fragments. (Weaver et al. 2006)

1985). They may have once been a single comet that broke apart and then experienced slightly different orbital evolutions. Matonti et al. (2019) noted evidence of fractures near the "neck" of 67P that may indicate enhanced erosion and the possibility that 67P will break into two comets in the future.

Weissman (1980) found that dynamically new long-period comets split ∼10% of the time during their discovery apparitions, with older, returning LPCs splitting ∼4% per perihelion passage, and JFCs splitting ∼1% per perihelion passage. A review of the split comets listed in Boehnhardt (2004) suggests that these numbers are ∼4.5% and ∼3.5% per perihelion passage for the dynamically new and returning LPCs, respectively.

Weissman (1979) modeled the physical and dynamical evolution of LPCs from the Oort cloud and showed that random disruption accounted for the loss of ∼ 27% of LPCs entering the planetary system, the second most common loss mechanism after dynamical ejection.

6.2 Tidal Disruption

Cometary nuclei can be gravitationally disrupted if they pass within the Roche limits of large bodies such as the Sun or the giant planets. Since such close approaches are typically rare, this is not a commonly observed phenomenon. However, the Kreutz group of sungrazing comets was recognized by Kreutz (1888) and eight naked-eye Kreutz comets were discovered between 1843 and 1970 (Marsden 1967, 1989). Kreutz group members typically have perihelia within one solar radius of the solar photosphere, well within the solar Roche radius. They are likely the result of tidal splitting events on previous perihelion distances. Their high orbital inclinations, ∼139–144°, do not allow them to pass close to any of the planets.

Comet Ikeya-Seki (C/1965 S1) was a bright Kreutz group comet discovered in 1965. It passed perihelion at a distance of 0.007786 AU, or 1.67 solar radii (Kronk 1984). Just before perihelion it appeared to split into at least three pieces. One fragment faded rapidly but the second fragment persisted until both it and the main nucleus faded from view.

In 1979 the orbiting SOLWIND coronagraph discovered six Kreutz group comets (Michels et al. 1982; Sheeley et al. 1982) that were too faint to be observed from the ground. None of those comets were seen to survive perihelion passage. This was followed by the Solar Maximum and SOHO (Solar and Heliospheric Observatory) missions, launched in 1980 and 1995, respectively. SOHO has discovered over 3,000 comets, mostly in Kreutz-type orbits (Biesecker et al. 2002; Knight et al. 2010). Most of the small comets discovered by

SOHO did not survive perihelion passage. Other comets discovered in sun-grazing orbits were the Marsden and Kracht groups but these are far less numerous than the Kreutz group.

Although the Kreutz group progenitor nucleus was almost certainly disrupted by tidal forces, one must also realize that the sun-grazing comets suffer intense heating during their very close approaches to the Sun. This heating is great enough to vaporize iron and mineral grains. Weissman (1983) showed that a typical comet would lose at least ∼15 m in radius during a close passage with the Sun. Since many of the sun-grazing comets appear to be smaller than that (Biesecker et al. 2002; Knight et al. 2010), their total destruction can be achieved through thermal effects alone, not even considering gravitational tides.

Extreme nucleus heating could be ruled out in the case of two comets that tidally disrupted due to close passages to Jupiter. Comet 16P/Brooks 2 (1889 N1) was discovered in 1889 and multiple nuclei were observed near the main comet. An integration of its orbit backward in time showed that it had passed within 0.001 AU of Jupiter in 1886, or ∼2.1 Jupiter radii, well inside the orbit of Io (Kronk 1984). This strongly suggested that the nucleus was tidally disrupted during its close passage with Jupiter.

Comet Shoemaker-Levy 9 was discovered in 1993 and was found to be at least 9 separate nuclei (later increased to 21) in a straight line (Shoemaker et al. 1993). Orbit determinations showed that the multiple nuclei were in orbit around Jupiter and had most likely been captured as a single parent nucleus around 1929 ± 9 years (Chodas and Yeomans 1996). Moreover, the orbit reconstruction showed that the comet had passed within Jupiter's Roche limit at 1.6 Jupiter radii in 1992, and that the multiple nuclei would impact Jupiter on their next perijove passage. Asphaug and Benz (1994, 1996) showed that the multiple nuclei could be explained if the nucleus was a weakly-bonded rubble pile that disrupted at perijove and then gravitationally reassembled into multiple nuclei. Interestingly, the final number of reassembled nuclei depended on the bulk density of the progenitor nucleus and 21 fragments suggested an original bulk density of $\sim 600~\mathrm{kg\,m^{-3}}$ (other densities were possible depending on the nucleus rotation state). This was again pre-Rosetta evidence of the low bulk density of cometary nuclei. Subsequent reconstruction of the impact events on Jupiter suggested that the progenitor nucleus was ∼1.5 km in diameter (Asphaug and Benz 1996).

6.3 Loss/Burial of All Volatiles

The pre-Rosetta view of comets was that they were conglomerates of ice, silicate dust, and organic dust grains brought together in the Solar Nebula into small bodies several kilometers in diameter (Whipple 1950). These objects slowly lost their ices and dust until they dwindled down to nothing, or they left deposits of large non-volatile grains on their surfaces that eventually choked off all activity, not allowing insolation to penetrate to depths where ices might still be present. Thermal models showed that such deposits needed to be only tens of meters thick to turn active comets into asteroidal-appearing objects (Brin and Mendis 1979; Fanale and Salvail 1984).

In the case of active comets with known nucleus radii, one could define the "active fraction," the percentage of the nucleus surface that needed to be active in order to provide the observed water production rate for that comet (A'Hearn et al. 1995; Gutiérrez et al. 2003). Active comets like 1P/Halley had an active fraction of ∼30% of the sunlit hemisphere, whereas typical JFCs had active fractions on the order of only ∼1%. Spacecraft flyby images of comet nuclei showed that this dichotomy of apparently active and inactive regions was seen on several nuclei. This was taken as proof that comets could eventually evolve to completely inactive objects.

Studies of the possible evolution of comets into asteroids (Weissman et al. 2002) showed that there were many objects in the near-Earth asteroid (NEA) population that might be dormant cometary nuclei, and that these objects usually had primitive-type taxonomic identifications, i.e., C, D, F, or low albedos. Weissman et al. (2002) estimated that 6% of the NEA population could be dormant comets. Dynamical simulations of the possible sources of the NEO population (Bottke et al. 2002) showed that NEOs with a high probability of a JFC origin tended to be primitive taxonomic types. Similarly, Fernández et al. (2001) compared measured albedos for 14 comet nuclei and 10 NEOs with Tisserand parameters,[1] $T < 3$, and 34 NEOs with $T > 3$. They showed that all of the comets and 9 out of 10 of the NEOs with $T < 3$ had albedos ≤ 0.07, while most of the NEOs with $T > 3$ had albedos >0.15.

DeMeo and Binzel (2006) obtained spectra of 32 NEOs with $T < 3$ and found that 17 of 32 objects had primitive taxonomic types. They estimated that ~16% of the NEO population had taxonomic types and Tisserand parameters consistent with a cometary origin.

It appears likely that cometary nuclei can slowly evolve to an asteroidal state. But the fraction of comets that do so, versus the fraction that disintegrates completely cannot yet be determined. Nonetheless, this is likely to be one of the major end states for cometary nuclei.

6.4 Collision with a Planet or the Sun

The probability of a comet striking a planet in a circular orbit is given by Öpik (1951) by

$$p = s^2 U / \left(\pi \sin i \, |U_x|\right) \tag{6.1}$$

where s is the capture radius of the target planet (including gravitational focusing), U is the encounter velocity of the comet with the planet (also known as *V-infinity*), i is the inclination of the comet's orbit relative to the planet's orbit and U_x is the component of the encounter velocity in the radial direction.

Kessler (1981) provided similar equations for estimating the impact probability for planets in elliptical orbits. Weissman (1982) used these equations to estimate a mean impact probability of 2.2×10^{-9} for Earth-crossing LPCs (per perihelion passage). Similar calculations find that Jupiter, the largest planet, also has the largest impact probability for LPCs, $p = 9.5 \times 10^{-8}$, approximately four times that for the other seven planets combined.

Impact probabilities for JFCs are more difficult to assess, in particular for the giant planets, because we do not know the orbital distributions of planet-crossing objects in that region of the planetary system. Based on calculations for the known JFCs and the terrestrial planets, typical JFC impact probabilities are about three times greater than for LPCs (Weissman 1982; Shoemaker et al. 1995; Levison et al. 2000).

Given these very low impact probabilities, collisions with planets is an unlikely end-state for cometary nuclei. Given the small size of the targets, collisions with satellites, asteroids and comets will be even less probable than for the planets.

Cometary orbits that impact the Sun are rare and are dominated by the Kreutz group comets (see Sect. 6.2). Technically, most of the Kreutz group members have perihelia greater than the Sun's photospheric radius and are destroyed by tidal disruption and intense heating. There do exist dynamical paths for sending comets onto sun-impacting trajectories (Jones et al. 2018) but few have been observed to do so. Solar impact is an unlikely end-state for comets.

[1]The Tisserand parameter, T, is a pseudo-constant of the motion in the restricted 3-body problem (Sun-Jupiter-comet) that is used to identify returning JFCs even though their orbits may have been changed by a close approach to Jupiter. Typically, comets have T values < 3, while asteroids have $T > 3$.

7 Discussion

ESA's Rosetta/Philae mission to comet 67P/Churyumov-Gerasimenko has yielded a bonanza of new information on comet nuclei, comet comae, and their interaction with the solar wind. Rosetta/Philae has provided detailed information on the composition of dust and ice in the coma, the bulk density, porosity, rotational properties and mass of the nucleus, the morphology of the nucleus surface and the active processes acting on it, and much more. But has Rosetta provided us new insights into how comet nuclei formed? Yes, we know far more about a typical comet nucleus, information that constrains models of nucleus formation. But, no, we do not yet know enough to discriminate between the currently competing hypotheses.

Pre-Rosetta models for cometary nuclei (Weissman 1986; Donn and Hughes 1986) predicted that the nuclei would be irregular objects with substantial internal voids. The first prediction has been confirmed by several nucleus flyby missions and by Rosetta. But the CONSERT radar instrument on Rosetta/Philae detected no large voids, at least none larger than ∼9 meters in size (Ciarletti et al. 2017a). That was a very unexpected result. Note that CONSERT only obtained two relatively shallow radar scans through the "head" (small lobe) of comet 67P. The spatial resolution limits of CONSERT cannot tell us about internal structure at scales $\lesssim$ 9 meters. So if there is macro-porosity in the nucleus, the only evidence we have is that it does not appear to be present on size scales $>$ 9 meters.

Yet the high porosity numbers determined for the bulk nucleus, 70% to 85% (Pätzold et al. 2016), suggests that there must be substantial micro-porosity. We see that micro-porosity in the COSIMA images of dust aggregates (Merouane et al. 2016), the MIDAS high resolution examination of dust grains (Bentley et al. 2016; Mannel et al. 2016; Mannel et al. 2019), and the possible existence of extremely porous dust aggregates in the 67P coma (Fulle et al. 2015). Can these examples of micro-porosity account completely for the bulk porosity of the 67P nucleus or must there also be some macro-porosity on size scales of 1 mm to 9 meters? The answer is, we don't know.

An important fact to consider is that both the hierarchical accretion and pebble growth hypotheses describe hierarchical accretion as the first step in producing particles up to 1 mm to 10 cm in size. For our purposes they are the same up to that size range. The question is what happens afterwards that leads to comet nuclei several kilometers in radius. In Sects. 2 and 3 we described these two competing hypotheses. Advocates for each hypothesis point to Rosetta/Philae results that they regard as supporting their ideas. But there are also critics of each process and we begin here by describing those criticisms.

7.1 Issues with the Hierarchical Growth of Planetesimals

Although the hierarchical growth of planetesimals described in Sect. 2 can explain a variety of observables among comets and Kuiper belt objects, it faces at least four serious issues:

Fragmentation Empirical evidence from laboratory experiments primarily performed for aggregates consisting of μm-sized silica monomers shows that fragmentation, i.e., a net mass loss and not mass gain (see Blum and Wurm 2008 and Güttler et al. 2010) is the dominant outcome in the majority of the collisions in the Davidsson et al. (2016) model. Bukhari Syed et al. (2017) derived a dust-aggregate collision model for macroscopic aggregates and collision velocities in the $\mathrm{m\,s^{-1}}$ regime. If we compare the impact energy per unit target mass, $E_{\mathrm{imp}}/m_{\mathrm{t}}$, from the Davidsson et al. (2016) model (see Table 1) with the dust-aggregate strength Q^* extrapolated from the Bukhari Syed et al. (2017) model (see their Eq. (10)), we see that $E_{\rm imp}/m_{\rm t} \gg Q^*$ for all bodies with $D \gtrsim 1$ m. Thus, if no consolidation (e.g., by sintering or melting) occurs, which would considerably increase Q^* above the values given by Bukhari et al. (2017), collisions will result in fragmentation. As Blum (2018) showed, the parameter space for mass gain of the target body is very limited.

Erosion The situation is even worse if one considers another physical process that only recently has been identified as a growth limiter. Schräpler et al. (2018) experimentally investigated the effect of impacts of very small dust particles and aggregates into large target aggregates. They showed that erosion, i.e., mass loss from the target, is the main result for impact speeds above a few $\mathrm{m\,s^{-1}}$. Based on their empirical laboratory data, Schräpler et al. (2018) showed in a numerical simulation that even under the assumptions that all other (non-eroding) collisions would result in perfect sticking, the maximum achievable aggregate size is on the order of 10 cm. This is because any erosional impact releases more small particles than it consumes so that an avalanche effect sets in. In an earlier work, Gundlach and Blum (2015) showed that erosion can also occur for µm-sized water-ice particles at low temperatures. However, see the discussion on "Ices" in Sect. 7.2 concerning the possibility that the stickiness of ice in general, and amorphous water ice in particular, may remove the fragmentation and erosion barriers.

Timescale The two most important timescale limitations with respect to mass growth in the pre-planetesimal phase are the radial drift, caused by friction with the sub-Keplerian gas disk, and the dissipation of the nebula gas. While the former is already important for aggregates in the mm- to cm-size range (see Lorek et al. 2018), the latter limits the formation of planetesimals by hierarchical growth. With realistic growth physics, Garaud et al. (2013) showed that bodies with sizes of $\sim$100 m can form at 1 AU, but farther out, at $\sim$30 AU in the disk, no growth beyond $\sim$10 m size was possible within $\sim 10^6$ years. Similarly, Windmark et al. (2012a, 2012b) calculated that $\sim$100 m-sized bodies can form within $\sim 10^6$ years at 3 AU, but nothing bigger than that. Note however that the Primordial Disk likely survived much longer than the 10^6 years used in these simulations so there was time to grow larger bodies, though accretion of pebbles is eventually limited by pebble drift into the Sun.

Strength If bodies formed by hierarchical growth, impact pressures are always high enough to compact the material to porosities of $\sim$60% (Weidling et al. 2009) and turn the growing planetesimals into homogeneous bodies. It was shown experimentally that the tensile strength (inner cohesion) of such bodies is on the order of 1–10 kPa (Gundlach et al. 2018). Such high strength values are a severe problem for the activity of comets.

7.2 Issues with the Growth of Planetesimals from Pebbles

Here we identify some serious issues with the growth of planetesimals from pebbles.

Numerical Simulations of the gravitational collapse of pebble swarms show that this process typically produces two bodies of similar size that orbit about their common center of mass at distances that are very large compared to the body diameters (Nesvorný et al. 2010). The high fraction of ultrawide binaries (diameter $D = 100$ km class bodies separated by 10^3–10^5 km) among the dynamically cold Kuiper belt objects (Stephens and Noll 2006) suggests that this mechanism indeed was active in the early Solar System. The collapse time of a $D = 100$ km body is $\sim$25 yr but the collapse time of a comet-sized $D = 1$ km body is several times 10^3 yr (Wahlberg Jansson and Johansen 2014). The time needed to form comet-sized objects through pebble swarm collapse is so long that these swarms may disperse or merge into much larger swarms, before they have the time to form small objects.

Computational Limits Magnetohydrodynamical computer models of Solar Nebula gas and plasma interacting with pebbles do not yet have the resolution to demonstrate that small pebble swarms actually form and that they survive long enough against dissipation or growth to much larger size before collapsing to $D = 1$ km objects. The smallest swarms forming in the highest-resolution simulations published thus far can create $D = 60$ km objects (Johansen et al. 2015). Such bodies would likely not preserve the low bulk densities and high porosities we see for cometary nuclei, as shown in Sect. 3.2. Therefore, it is not yet known whether pebble swarm collapse is a viable mechanism for forming bodies the size of known comet nuclei.

Heating Because the pebble swarm collapse mechanism allows bodies to reach their final size on short time scales, heating from decaying short-lived radio-nuclides like ^{26}Al may be strong. The high bulk density of some small, dynamically-cold Kuiper belt objects, like (66652) Borasisi with primary diameter $D_1 = 126^{+25}_{-51}$ km and $\rho = 2100^{+2600}_{-1200}$ kg m^{-3} (Vilenius et al. 2014) suggest that loss of porosity due to radiogenic heating and ice melting probably occurred. Comet nuclei could not have experienced such heating without losing their observed rich inventory of supervolatiles (e.g., Prialnik et al. 1987; Merk and Prialnik 2003, 2006; Podolak and Prialnik 2006). This suggests that comets may have grown slowly and reached their final sizes late.

Johansen and Mac Low (2009) show that pebble swarm formation and collapse may require high disk metallicities, only achieved at the end of the $\sim$3 Myr Solar Nebula lifetime (Zuckerman et al. 1995; Haisch et al. 2001; Sicilia-Aguilar et al. 2006). This would solve the ^{26}Al problem but introduces new difficulties because the pebbles have rapid radial drift that cannot proceed for millions of years without emptying the outer planets region. Furthermore, direct exposure to protosolar radiation during excursions to high disk scale heights, likely to happen at some point during millions of years of evolution, leads to supervolatile loss in hours. Icy materials need to be protected inside a body much larger than the diurnal and orbital thermal skin depths of pebbles.

Ices Ros and Johansen (2013) showed that the role of ices could be very important in increasing the growth rate and the eventual sizes of pebbles. In their model, water ice vapor condenses onto particles beyond the snowline (see Introduction). Decimeter refractory particles can grow to meter sizes or larger in only a few times 10^3 years. This model can thus help hierarchically grown particles jump the 1 meter barrier and continue to grow to larger sizes. That would make streaming instabilities inefficient in creating pebble swarms because of the difficulty of concentrating such larger bodies. Bridges et al. (1996) showed that particles covered with an ice frost could have increased stickiness as compared with refractory particles. Wettlaufer (2010) proposed that amorphous ice particles, warmed by collisions, could also increase stickiness.

7.3 Issues with Collisional Evolution

As described in Sect. 4, the best current models for the collisional environment of comets in the Primordial Disk and during their dispersal to the Kuiper belt, Scattered disk and Oort cloud (Morbidelli and Rickman 2015; Stern and Weissman 2001; Charnoz and Morbidelli 2003, 2007) suggest that comets suffered serious collisional evolution during that time. However, those estimates are based on some poorly known values, such as the total number of comet nuclei in the Primordial Disk, their orbital distributions and their size distributions.

The best estimates for the slope of the cumulative size distribution for the JFCs give values near −2 (Snodgrass et al. 2011; Meech et al. 2004) and are in good agreement with slope estimates for the size distributions found in theoretical predictions of the collisional evolution of planetesimals in the strength regime by O'Brien and Greenberg (2005). However, the agreement is not good for the predictions in Fig. 1 (left), which find a cumulative slope of −3 for the JFCs. Note that the JFC size distribution is only well known for radii between ∼1.2 and ∼10 km. Both observational and theoretical investigations need to continue in this area to further improve our understanding of its effects on comet nuclei.

7.4 Future Missions and Investigations

Rosetta has clearly told us more about comets than any previous space mission. It has demonstrated the importance of long-duration rendezvous missions with the capability to study cometary nuclei and cometary phenomena over extended periods of time. Below we discuss what future missions may be able to accomplish.

The next logical mission to a comet is Comet Surface Sample Return (CSSR). Such a mission, CAESAR (Comet Astrobiology Exploration Sample Return) was under consideration by NASA for its New Frontiers Program but it was not selected for development.. The goal of CSSR is to return a comet surface sample of 80–800 grams to Earth for study in terrestrial laboratories. The current capabilities of those laboratories far surpass that of any instruments that could be flown on a comet rendezvous mission. Those capabilities would have an additional 15–20 years to continue to improve while the mission is formulated, assembled, launched and flown. Returned cometary samples have the potential to tell us far more about the composition of cometary nuclei, the physical process of accretion and the formation of the low-volatility nucleus surface crusts. The samples might even contain "pebbles" if they exist.

The next most discussed comet mission after CSSR is Comet Cryogenic Sample Return (CCSR), like the Triple-F mission proposed to ESA several years ago (Küppers et al. 2009). This mission would dig below the nucleus surface to obtain samples that contain cometary ices. The collection depth would need to be at least several orbital thermal skin depths, $\gtrsim 3$ meters. The sample would need to be maintained at its cryogenic temperature, <80 K (or colder) for the duration of the return flight to Earth, including atmospheric entry and capsule retrieval. Both the cryogenic sample collection below the nucleus surface and maintaining the sample at its collected temperature are major technological challenges that require substantial investments by national space agencies in the coming decade. Also, because of its complexity the CCSR mission would need to be a flagship mission with a multi-billion dollar/euro budget. A CCSR mission would tell us far more about the complete composition of cometary nuclei and the accretion process.

Both CSSR and CCSR will greatly improve our knowledge of comet nucleus composition and possibly its chemical evolution over time. It is unlikely that either mission could address nucleus stratigraphy. CSSR concepts usually collect samples with semi-violent methods, i.e., nitrogen bursts into the surface or a mechanical brush-wheel sampler. The collection method for CCSR is not yet determined. However, the deceleration forces of re-entry of the sample return capsule into the Earth's atmosphere would likely destroy any existing structures within the low-strength comet materials. This problem could be partially overcome if samples could be separately obtained from different depths below the nucleus surface and stored isolated from one another. Smaller structures may survive re-entry and so the returned samples may provide important clues to the accretion process at microscopic scales.

CCSR might also be valuable in answering one of the major questions concerning the origin of icy planetesimals: whether water ice existed in amorphous or crystalline form in the Solar Nebula, or whether the water-ice grains were formed in the precursor molecular cloud or by condensation in the Solar Nebula. Another question of great interest for planetesimal-formation studies is the composition of the organic component and its stickiness in grain-grain collisions. If the organic particles were stickier than the silicate or water-ice particles, a direct collisional growth path from dust to planetesimals seems feasible with no need for pebbles and gravitational collapse. However, a stickier material than silicates and water ice would possibly increase internal cohesion within the comet nucleus so that dust activity might be impossible. The same issue may also be addressed regarding the stickiness of amorphous water-ice grains.

Like CSSR, CCSR may need to be so focused on sample collection and preservation that it will be unable to carry other scientific instruments that could address comet origin and evolution. So what can we do to address the issues discussed herein? It may require a separate rendezvous mission, like Rosetta, but carrying specific instruments to address origin and evolution. One choice would be a powerful radar instrument such as the Shallow Radar (SHARAD, Seu et al. 2007) on the Mars Reconnaissance Orbiter spacecraft. SHARAD could probe the interior structure of a cometary nucleus at all locations and not just the limited ray paths possible for CONSERT. SHARAD has a vertical resolution of 15 meters and a penetration depth of $\sim$1 km in the Martian soil; the latter number should be significantly greater in the ice-hydrocarbon-silicate mix of a comet nucleus. Thus, SHARAD may be able to map the interior structure of the entire nucleus for a typical 2–4 km diameter body.

In its current configuration SHARAD does not have the spatial resolution necessary to detect pebbles. Thus, another instrument worth considering is the WISDOM (Water Ice and Subsurface Deposit On Mars) radar on the ExoMars Rover, planned for launch in 2020. WISDOM (Ciarletti et al. 2017b) operates at several wavelengths, the shortest of which is 0.1 m (30 times finer than CONSERT) and can penetrate 3 m into the rocky soil of Mars. As noted above, it should be able to penetrate significantly deeper into the ice- and carbon-rich interior of a comet nucleus. Note that WISDOM requires a landed package or preferably a surface rover to accomplish its investigation. Also, the spatial resolution of WISDOM is not sufficient to resolve individual pebbles if the pebbles are less than tens of cm in diameter. Thus even higher resolution radars may be needed.

A landed instrument package could also address many of the Philae objectives that could not be addressed because of Philaes's final landed orientation. With the knowledge gained from study of Philae's bouncing, a lander package could be designed that would more likely remain at its targeted landing site. Again, the capabilities of the landed package would be greatly enhanced if it could be a rover rather than a fixed lander. Updated versions of all of the instruments on Philae would be highly desirable. This would include thermal probes to measure the temperature versus depth, penetrator instruments that could measure the strength of the surface materials, a drill, and compositional instruments to measure the composition of the near-surface materials. Finally, a high resolution camera system might be able to resolve individual pebbles on the surface.

Current thinking for CSSR is to return to 67P because of Rosetta's extensive mapping and the nucleus' known qualities. However, we propose that any future rendezvous mission as described above should visit a different comet nucleus to address questions of nucleus diversity as well as to provide a second target choice for the future CCSR mission. Having seen one cometary nucleus in great detail, 67P, it is too tempting to apply the Rosetta and Philae results in general to all comet nuclei. The several flyby missions to comets so far have shown them to be a very diverse population with different degrees of activity and surface evolution, and highly different topographies. A priority scientific objective is to visit as many nuclei as possible and to observe each with the intensity of Rosetta/Philae. As of this date there have already been six asteroid orbiters: NEAR, Hayabusa, Dawn at Vesta, Dawn at Ceres, Haybusa 2, and Osiris-REX. We need many more orbiter missions to comets.

In addition to new comet missions, future theoretical and laboratory investigations as well as computer simulations and telescopic programs will continue to improve our understanding of comet nuclei and how they formed. It will be valuable to see if pebble accretion scenarios can be extended down to actual comet nucleus sizes, i.e., radii < 10 km, while maintaining reasonable formation times. It will be interesting to understand better the role of amorphous water (and other) ices in possibly achieving more rapid accretion times as well as improving the ability of hierarchical accretion to cross the $\sim$1 meter barrier that has stymied researchers for decades. Increasingly deep small body surveys of the solar system will improve our understanding of the size distributions of comets in the two major reservoirs as well as their orbital and spatial distributions. We are not foolish enough to try and predict all or even some of the future discoveries about comets and their origin but we do look eagerly toward them.

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References

C.P. Abod, J.B. Simon, R. Li, P.J. Armitage, A.N. Youdin, K.A. Kretke, The mass and size distribution of planetesimals formed by the streaming instability. II. The effect of the radial gas pressure gradient. Astrophys. J. **883**(2), 192 (2018). http://adsabs.harvard.edu/abs/2018arXiv181010018A

I. Adachi, C. Hayashi, K. Nakazawa, The gas drag effect on the elliptic motion of a solid body in the primordial solar nebula. Prog. Theor. Phys. **56**(6), 1756–1771 (1976)

M.F. A'Hearn, R.C. Millis, D.G. Schleicher, D.J. Osip, P.V. Birch, The ensemble properties of comets: results from narrowband photometry of 85 comets. Icarus **118**, 223–270 (1995)

M.F. A'Hearn, M.J.S. Belton, W.A. Delamere, L.M. Feaga, D. Hampton, J. Kissel, K.P. Klaasen, L.A. McFadden, K.J. Meech, H.J. Melosh, P.H. Schultz, J.M. Sunshine, P.C. Thomas, J. Veverka, D.D. Wellnitz, D.K. Yeomans, S. Besse, D. Bodewits, T.J. Bowling, B.T. Carcich, S.M. Collins, T.L. Farnham, O. Groussin, B. Hermalyn, M.S. Kelley, M.S. Kelley, J.-Y. Li, D.J. Lindler, C.M. Lisse, S.A. McLaughlin, F. Merlin, S. Protopapa, J.E. Richardson, J.L. Williams, EPOXI at comet Hartley 2. Science **332**, 1396–1400 (2011)

K. Altwegg, H. Balsiger, A. Bar-Nun, J.-J. Berthelier, A. Bieler, P. Bochsler, C. Briois, U. Calmonte, M.R. Combi, H. Cottin, J. De Keyser, F. Dhooghe, B. Fiethe, S.A. Fuselier, S. Gasc, T.I. Gombosi, K.C. Hansen, M. Haessig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, B. Marty, O. Mousis, T. Owen, H. Reme, M. Rubin, T. Semon, C.-Y. Tzou, J.H. Waite, P. Wurz, Prebiotic chemicals—amino acids and phosphorus—in the coma of comet 67P/Churyumov-Gerasimenko. Sci. Adv. **2**, e1600285 (2016)

P. Andre, T. Montmerle, From T Tauri stars to protostars: circumstellar material and young stellar objects in the Ophiuchi cloud. Astron. J. **420**, 837–862 (1994)

E. Asphaug, W. Benz, Density of comet Shoemaker-Levy 9 deduced by modeling of the parent rubble pile. Nature **370**, 120–124 (1994)

E. Asphaug, W. Benz, Size, density and structure of comet Shoemaker-Levy 9 inferred from the physics of tidal breakup. Icarus **121**, 225–248 (1996)

M. Asplund, N. Grevesse, A.J. Sauval, P. Scott, The chemical composition of the Sun. Annu. Rev. Astron. Astrophys. **47**, 481–522 (2009)

N. Attree, O. Groussin, L. Jorda, D. Nébouy, N. Thomas, Y. Brouet, E. Kührt, F. Preusker, F. Scholten, J. Knollenberg, P. Hartogh, H. Sierks, C. Barbieri, P. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, M.F. A'Hearn, A.-T. Auger, M.A. Barucci, J.-L. Bertaux, I. Bertini, D. Bodewits, S. Boudreault, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, J. Deller, M.R. El-Maarry, S. Fornasier, M. Fulle, P.J. Gutiérrez, C. Güttler, S. Hviid, W.-H. Ip, G. Kovacs, J.R. Kramm, M. Küppers, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, S. Lowry, S. Marchi, F. Marzari, S. Mottola, G. Naletto, N. Oklay, M. Pajola, I. Toth, C. Tubiana, J.-B. Vincent, X. Shi, Tensile strength of 67P/Churyumov-Gerasimenko nucleus material from overhangs. Astron. Astrophys. **611**, A33 (2018)

A.-T. Auger, O. Groussin, L. Jorda, S. Bouley, R. Gaskell, P.L. Lamy, C. Capanna, N. Thomas, A. Pommerol, H. Sierks, C. Barbieri, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.F. A'Hearn, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, M.R. El-Maarry, S. Fornasier, M. Fulle, P.J. Gutierrez, C. Güttler, S. Hviid, W.-H. Ip, J. Knollenberg, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, S. Marchi, F. Marzari, M. Massironi, H. Michalik, G. Naletto, N. Oklay, M. Pajola, L. Sabau, C. Tubiana, J.-B. Vincent, K.-P. Wenzel, Geomorphology of the Imhotep region on comet 67P/Churyumov-Gerasimenko from OSIRIS observations. Astron. Astrophys. **583**, A35 (2015)

A.-T. Auger, O. Groussin, L. Jorda, M.R. El-Maarry, S. Bouley, A. Sejourne, R. Gaskell, C. Capanna, B. Davidsson, S. Marchi, S. Höfner, P.L. Lamy, H. Sierks, C. Barbieri, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.F. A'Hearn, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, S. Fornasier, M. Fulle, P.J. Gutierrez, C. Güttler, S. Hviid, W.-H. Ip, J. Knollenberg, J.-R. Kramm, E. Kührt, M. Küppers, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, M. Massironi, H. Michalik, G. Naletto, N. Oklay, A. Pommerol, L. Sabau, N. Thomas, C. Tubiana, J.-B. Vincent, K.-P. Wenzel, Meter-scale thermal contraction crack polygons on the nucleus of comet 67P/Churyumov-Gerasimenko. Icarus **301**, 173–188 (2018)

M.J.S. Belton, The size-distribution of scattered disk TNOs from that of JFCs between 0.2 and 15 km effective radius. Icarus **231**, 168–182 (2014)

M.J.S. Belton, P. Thomas, J. Veverka, P. Schultz, M.F. A'Hearn, L. Feaga, T. Farnham, O. Groussin, J.-Y. Li, C. Lisse, L. McFadden, J. Sunshine, K.J. Meech, W.A. Delamere, J. Kissel, The internal structure of Jupiter family cometary nuclei from Deep Impact observations: the "talps" or "layered pile" model. Icarus **187**, 332–344 (2007)

M.S. Bentley, R. Schmied, T. Mannel, . co-authors, Aggregate dust particles at comet 67P/Churyumov-Gerasimenko. Nature **537**, 73–75 (2016)

D.A. Biesecker, P. Lamy, O.C. St. Cyr, A. Llebaria, R.A. Howard, Sungrazing comets discovered with the SOHO/LASCO coronagraphs 1996–1998. Icarus **157**, 323–348 (2002)

T. Birnstiel, L. Ricci, F. Trotta, C.P. Dullemond, A. Natta, L. Testi, C. Dominik, T. Henning, C.W. Ormel, A. Zsom, Testing the theory of grain growth and fragmentation by millimeter observations of protoplanetary disks. Astron. Astrophys. **516**, L14 (2010)

D. Bischoff, B. Gundlach, M. Neuhaus, J. Blum, Experiments on cometary activity: ejection of dust aggregates from an evaporating water–ice surface. Mon. Not. R. Astron. Soc. **483**, 1202–1210 (2019)

J. Blum, Dust agglomeration. Adv. Phys. **55**, 881–947 (2006)

J. Blum, Dust evolution in protoplanetary discs and the formation of planetesimals. What have we learned from laboratory experiments? Space Sci. Rev. **214**, 52 (2018)

J. Blum, G. Wurm, The growth mechanisms of macroscopic bodies in protoplanetary disks. Annu. Rev. Astron. Astrophys. **46**, 21–56 (2008)

J. Blum, G. Wurm, S. Kempf, T. Poppe, H. Klahr, T. Kozasa, M. Rott, T. Henning, J. Dorschner, R. Schräpler, H.U. Keller, W.J. Markiewicz, I. Mann, B.A. Gustafson, F. Giovane, D. Neuhaus, H. Fechtig, E. Grün, B. Feuerbacher, H. Kochan, L. Ratke, A. El Goresy, G. Morfill, S.J. Weidenschilling, G. Schwehm, K. Metzler, W.-H. Ip, Growth and form of planetary seedlings: results from a microgravity aggregation experiment. Phys. Rev. Lett. **85**, 2426–2429 (2000)

J. Blum, B. Gundlach, S. Mühle, J.M. Trigo-Rodriguez, Comets formed in solar nebula instabilities!—An experimental and modeling attempt to relate the activity of comets to their formation process. Icarus **235**, 156–169 (2014)

J. Blum, B. Gundlach, S. Mühle, J.M. Trigo-Rodriguez, Corrigendum to "Comets formed in solar-nebula instabilities!—An experimental and modeling attempt to relate the activity of comets to their formation process" [Icarus 235 (2014) 156–169]. Icarus **248**, 135–136 (2015)

J. Blum, B. Gundlach, M. Krause, M. Fulle, A. Johansen, J. Agarwal, I. von Borstel, X. Shi, X. Hu, M.S. Bentley, F. Capaccioni, L. Colangeli, V. Della Corte, N. Fougere, S.F. Green, S. Ivanovski, T. Mannel, S. Merouane, A. Migliorini, A. Rotundi, R. Schmied, C. Snodgrass, Evidence for the formation of comet 67P/Churyumov- Gerasimenko through gravitational collapse of a bound clump of pebbles. Mon. Not. R. Astron. Soc. **469**, S755–S773 (2017)

H. Boehnhardt, Split comets, in *Comets II*, ed. by M.C. Festou, U. Keller, H.A. Weaver (Univ. Arizona Press, Tucson, 2004), pp. 301–316

H. Boehnhardt, H.U. Kaeufl, P. Goudgrooij, J. Storm, J. Manfroid, K. Reinsch, The break-up of periodic comet Schwassmann-Wachmann 3: image documents from La Silla telescopes. Messenger **84**, 26–29 (1996)

W.F. Bottke, A. Morbidelli, R. Jedicke, J.-M. Petit, H.F. Levison, P. Michel, T.S. Metcalfe, Debiased orbital and absolute magnitude distribution of the near-Earth objects. Icarus **156**, 399–433 (2002)

W.F. Bottke, D.D. Durda, D. Nesvorný, R. Jedicke, A. Morbidelli, D. Vokrouhlický, H. Levison, The fossilized size distribution of the main asteroid belt. Icarus **175**, 111–140 (2005)

R. Brasser, A. Morbidelli, Oort cloud and Scattered Disc formation during a late dynamical instability in the Solar System. Icarus **225**, 40–49 (2013)

F.G. Bridges, K.D. Supulver, D.N.C. Lin, R. Knight, M. Zafra, Energy loss and sticking mechanisms in particle aggregation in planetesimal formation. Icarus **123**, 422–435 (1996)

G.D. Brin, D.A. Mendis, Dust release and mantle development in comets. Astron. J. **229**, 1095–1108 (1979)

J. Brisset, D. Heißelmann, S. Kothe, R. Weidling, J. Blum, Submillimetre-sized dust aggregate collision and growth properties. Experimental study of a multi-particle system on a suborbital rocket. Astron. Astrophys. **593**, A3 (2016)

D.E. Brownlee, Cosmic dust: collection and research. Annu. Rev. Earth Planet. Sci. **13**, 147–173 (1985)

D. Brownlee, D. Joswiak, G. Matrajt, Overview of the rocky component of Wild 2 comet samples: insight into the early solar system, relationship with meteoritic materials and the differences between comets and asteroids. Meteorit. Planet. Sci. **47**(4), 453–470 (2012)

M. Bukhari Syed, J. Blum, K. Wahlberg Jansson, A. Johansen, The role of pebble fragmentation in planetesimal formation. I. Experimental study. Astrophys. J. **834**, 145 (2017)

A. Carusi, L. Kresak, E. Perozzi, G.B. Valsecchi, First results of the integration of motion of short-period comets over 800 years, in *Dynamics of Comets: Their Origin and Evolution*, ed. by A. Carusi, G.B. Valsechhi. (D. Reidel, Dordrecht, 1985), pp. 319–340

S. Charnoz, A. Morbidelli, Coupling of dynamical and collisional evolution of small bodies: an application to the early ejection of planetesimals from the Jupiter-Saturn reion. Icarus **166**, 141–156 (2003)

S. Charnoz, A. Morbidelli, Coupling dynamical and collisional evolution of small bodies. II. Forming the Kuiper belt, the Scattered Disk and the Oort Cloud. Icarus **188**, 468–480 (2007)

S.R. Chesley, M.J.S. Belton, B. Carcich, P.C. Thomas, J. Pittichova, K.P. Klaasen, J.-Y. Li, T.L. Farnham, S.D. Gillam, A.W. Harris, J. Veverka, An updated rotation model for Comet 9P/Tempel 1. Icarus **222**, 516–525 (2013)

P.W. Chodas, D.K. Yeomans, The orbital motion and impact circumstances of comet Shoemaker-Levy 9, in *The Collision of Comet Shoemaker-Levy 9 and Jupiter*, ed. by K.S. Noll, H.A. Weaver, P.D. Feldman. Space Tel. Sci. Inst. (1996), pp. 1–30

V. Ciarletti, A.C. Levasseur-Regourd, J. Lasue, C. Statz, D. Plettemeier, A. Herique, Y. Rogez, W. Kofman, CONSERT suggests a change in local properties of 67P/Churyumov-Gerasimenko's nucleus at depth. Astron. Astrophys. **583**, A40 (2015)

V. Ciarletti et al., The WISDOM radar: unveiling the subsurface beneath the ExoMars rover and identifying the best locations for drilling. Astrobiology **17**, 565–584 (2017b)

V. Ciarletti, A. Herique, J. Lasue, A.-C. Levasseur-Regourd, D. Plettemeier, F. Lemmonier, C. Guiffaut, P. Pasquero, W. Kofman, CONSERT constrains the internal structure of 67P at a few meters size scale. Mon. Not. R. Astron. Soc. **469**, S805–S817 (2017a)

J.F. Cooper, E.R. Christian, R.R. Johnson, Heliospheric cosmic ray irradiation of Kuiper belt comets. Adv. Space Res. **21**, 1611–1614 (1998)

P. D'Alessio, N. Calvet, L. Hartmann, R. Franco-Hernández, H. Servín, Effects of dust growth and settling in T Tauri disks. Astrophys. J. **638**, 314–335 (2006)

B.J.R. Davidsson, P.J. Gutiérrez, Estimating the nucleus density of Comet 19P/Borrelly. Icarus **168**(2), 392–408 (2004)

B.J.R. Davidsson, P.J. Gutiérrez, Nucleus properties of Comet 67P/Churyumov-Gerasimenko estimated from non-gravitational force modeling. Icarus **176**(2), 453–477 (2005)

B.J.R. Davidsson, P.J. Gutiérrez, Non-gravitational force modeling of comet 81P/Wild 2. I. A nucleus bulk density estimate. Icarus **180**, 224–242 (2006)

B.J.R. Davidsson, P.J. Gutierrez, H. Rickman, Nucleus properties of Comet 9P/Tempel 1 estimated from non-gravitational force modeling. Icarus **187**, 306–320 (2007)

B.J.R. Davidsson, H. Sierks, C. Güttler, F. Marzari, M. Pajola, H. Rickman, M.F. A'Hearn, A.-T. Auger, M.R. El-Maarry, S. Fornasier, P.J. Gutiérrez, H.U. Keller, M. Massironi, C. Snodgrass, J.-B. Vincent, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, C. Feller, M. Fulle, O. Groussin, S.F. Hviid, S. Höfner, W.-H. Ip, L. Jorda, J. Knollenberg, G. Kovacs, J.-R. Kramm, E. Kührt, M. Küppers, F. La Forgia, L.M. Lara,

M. Lazzarin, J.J. Lopez Moreno, R. Moissl-Fraund, S. Mottola, G. Naletto, N. Oklay, N. Thomas, C. Tubiana, The primordial nucleus of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **592**, A63 (2016)

D. de Niem, E. Kührt, S. Hviid, B. Davidsson, Low velocity collisions of porous planetesimals in the early solar system. Icarus **301**, 196–218 (2018)

F. DeMeo, R.P. Binzel, Comets in the near-Earth object population. Bull. Am. Astron. Soc. **38**, 581 (2006)

C. Dominik, A.G.G.M. Tielens, The physics of dust coagulation and the structure of dust aggregates in space. Astrophys. J. **480**, 647–673 (1997)

B. Donn, The accumulation and structure of comets, in *Comets in the Post-Halley Era*, vol. 1, ed. by R.L. Newburn, M. Neugebauer, J. Rahe (Kluwer Academic Publishers, Dordrecht, 1991), pp. 335–355

B. Donn, D. Hughes, A fractal model of a cometary nucleus formed by random accretion, in *Proc. 20th ESLAB Symposium on the Exploration of Halley's Comet* (1986), pp. 523–524. ESA SP-250

M. Duncan, H.F. Levison, A scattered comet disk and the origin of Jupiter family comets. Science **276**, 1670–1672 (1997)

M. Duncan, T. Quinn, S. Tremaine, The origin of short-period comets. Astrophys. J. Lett. **328**, L69–L73 (1988)

M.R. El-Maarry, N. Thomas, A. Garcia Berna, R. Marschall, A.-T. Auger, O. Groussin, M. Massironi, S. Marchi, F. Preusker, F. Scholten, L. Jorda, E. Kührt, M. Hofmann, S. Hoefner, J. Deller (the OSIRIS team), Fractures on comet 67P/Churyumov-Gerasimenko observed by the Rosetta/OSIRIS camera. Geophys. Res. Lett. **42**(13), 5170–5178 (2015)

S. Espinasse, J. Klinger, C. Ritz, B. Schmitt, Modeling of the thermal behavior and of the chemical differentiation of cometary nuclei. Icarus **92**, 350–365 (1991)

F.P. Fanale, J.R. Salvail, An idealized short-period comet model: surface insolation, H2O flux, and mantle development. Icarus **60**, 476–511 (1984)

J.A. Fernández, New and evolved comets in the solar system. Astron. Astrophys. **96**, 26–35 (1981)

Y.R. Fernández, D.C. Jewitt, S.S. Shephard, Low albedos among extinct comet candidates. Astrophys. J. Lett. **553**, L197–L200 (2001)

S. Ferrari, L. Penasa, F. La Forgia, M. Massironi, G. Naletto, M. Lazzarin, S. Fornasier, P.H. Hasselmann, A. Lucchetti, M. Pajola, F. Ferri, P. Cambianica, N. Oklay, C. Tubiana, H. Sierks, P.L. Lamy, R. Rodrigo, D. Koschny, B. Davidsson, M.A. Barucci, J.-L. Bertaux, I. Bertini, D. Bodewits, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, J. Deller, M. Franceschi, E. Frattin, M. Fulle, O. Groussin, P.J. Gutiérrez, C. Güttler, S.F. Hviid, W.-H. Ip, L. Jorda, H.U. Keller, J. Knollenberg, E. Kührt, M. Küppers, L.M. Lara, J.J. López-Moreno, F. Marzari, X. Shi, E. Simioni, N. Thomas, J.-B. Vincent, The big lobe of 67P/Churyumov-Gerasimenko comet: morphological and spectrophotometric evidences of layering as from OSIRIS data. Mon. Not. R. Astron. Soc. **479**(2), 1555–1568 (2018)

M. Fulle, J. Blum, Fractal dust constrains the collisional history of comets. Mon. Not. R. Astron. Soc. **469**, S39–S44 (2017)

M. Fulle, V. Della Corte, A. Rotundi, P. Weissman, A. Juhasz, K. Szego, R. Sordini, M. Ferrari, S. Ivanovski, F. Lucarelli, M. Accolla, S. Merouane, V. Zakharov, E. Mazzotta Epifani, J.J. L_opez-Moreno, J. Rodríguez, L. Colangeli, P. Palumbo, E. Grün, M. Hilchenbach, E. Bussoletti, F. Esposito, S.F. Green, P.L. Lamy, J.A.M. McDonnell, V. Mennella, A. Molina, R. Morales, F. Moreno, J.L. Ortiz, E. Palomba, R. Rodrigo, J.C. Zarnecki, M. Cosi, F. Giovane, B. Gustafson, M.L. Herranz, J.M. Jerónimo, M.R. Leese, A.C. López-Jiménez, N. Altobelli, Density and charge of pristine fluffy particles from comet 67P/Churyumov-Gerasimenko. Astrophys. J. Lett. **802**, L12 (2015)

M. Fulle, J. Blum, S.F. Green, B. Gundlach, A. Henrique, F. Moreno, S. Mottola, A. Rotundi, C. Snodgrass, The refractory-to-ice mass ratio in comets. Mon. Not. R. Astron. Soc. **482**, 3326–3340 (2019)

P. Garaud, F. Meru, M. Galvagni, C. Olczak, From dust to planetesimals: an improved model for collisional growth in protoplanetary disks. Astrophys. J. **764**, 146 (2013)

S. Gasc, et al., Change of outgassing pattern of 67P/Churyumov-Gerasimenko during the March 2016 equinox as seen by ROSINA. Mon. Not. R. Astron. Soc. **469**, S108–S117 (2017)

R.W. Gaskell, L. Jorda, H. Sierks, P. Gutierrez, S. Faurschou Hviid, H.U. Keller, S. Mottola, C. Campanna (the OSIRIS team), Changes in Comet 67P/Churyumov-Gerasimenko during the ROSETTA Era—Shape, Topography and Rotation. AAS/DPS Meet. **48**, 11603 (2016)

K.-H. Glassmeier, H. Boehnhardt, D. Koschny, e. Kuhrt, I. Richter, The Rosetta mission: flying towards the origin of the solar system. Space Sci. Rev. **128**, 1–21 (2007)

R. Gomes, H.F. Levison, K. Tsiganis, A. Morbidelli, Origin of the cataclysmic Late Heavy Bombardment of the terrestrial planets. Nature **435**, 466–469 (2005)

O. Groussin, L. Jorda, A.-T. Auger, E. Kührt, R. Gaskell, C. Capanna, F. Scholten, F. Preusker, P. Lamy, S. Hviid, J. Knollenberg, U. Keller, C. Huettig, H. Sierks, C. Barbieri, R. Rodrigo, D. Koschny, H. Rickman, M.F. A'Hearn, J. Agarwal, M.A. Barucci, J.-L. Bertaux, I. Bertini, S. Boudreault, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, M.R. El-Maarry, S. Fornasier, M. Fulle, P.J. Gutiérrez, C. Güttler, W.-H. Ip, J.-R. Kramm, M. Küppers, M. Lazzarin, L.M. Lara, J.J. Lopez Moreno, S. Marchi, F. Marzari, M. Massironi, H. Michalik, G. Naletto, N. Oklay, A. Pommerol, M. Pajola, N. Thomas, I. Toth, C. Tubiana, J.-B. Vincent, Gravitational slopes, geomorphology, and material strengths of the nucleus of comet 67P/Churyumov-Gerasimenko from OSIRIS observations. Astron. Astrophys. **583**, A32 (2015)

B. Gundlach, J. Blum, The stickiness of micrometer-sized water-ice particles. Astrophys. J. **798**, 34 (2015)

B. Gundlach, J. Blum, Why are Jupiter-family comets active and asteroids in cometary-like orbits inactive? How hydrostatic compression leads to inactivity. Astron. Astrophys. **589**, A111 (2016)

B. Gundlach, J. Blum, H.U. Keller, Y.V. Skorov, What drives the dust activity of comet 67P/Churyumov-Gerasimenko? Astron. Astrophys. **583**, A12 (2015)

B. Gundlach, K.P. Schmidt, C. Kreuzig, D. Bischoff, F. Rezaei, S. Kothe, J. Blum, B. Grzesik, E. Stoll, The tensile strength of ice and dust aggregates and its dependence on particle properties. Mon. Not. R. Astron. Soc. **479**, 1273–1277 (2018)

P.J. Gutiérrez, R. Rodrigo, J.L. Ortiz, B.J.R. Davidsson, An investigation of errors in estimates of the cometary nuclei active area fractions. Astron. Astrophys. **401**, 755–761 (2003)

C. Güttler, J. Blum, A. Zsom, C.W. Ormel, C.P. Dullemond, The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? I. Mapping the zoo of laboratory collision experiments. Astron. Astrophys. **513**, A56 (2010)

K.E. Haisch, E.A. Lada, C.J. Lada, Disk frequencies and lifetimes in young clusters. Astrophys. J. **553**, L153–L156 (2001)

J.K. Harmon, M.C. Nolan, J.D. Giorgini, E.S. Howell, Radar observations of 8P/Tuttle: a contact-binary comet. Icarus **207**, 499–502 (2010)

A. Herique, W. Kofman, P. Beck, L. Bonal, I. Buttarazzi, E. Heggy, J. Lasue, A.C. Levasseur- Regourd, E. Quirico, S. Zine, Cosmochemical implications of CONSERT permittivity characterization of 67P/CG. Mon. Not. R. Astron. Soc. **462**, S516–S532 (2016)

M. Hirabayashi, D. Scheeres, S.R. Chesley, S. Marchi, J.W. McMahon, J. Steckloff, S. Mottola, S.P. Naidu, T. Bowling, Fission and reconfiguration of bilobate comets as revealed by 67P/Churyumov-Gerasimenko. Nature **534**, 352–355 (2016)

K.M. Housen, K. Holsapple, A crater and its ejecta: an interpretation of Deep Impact. Icarus **187**, 345–356 (2007)

X. Hu, B. Gundlach, I. von Borstel, J. Blum, X. Shi, Effect of radiative heat transfer in porous comet nuclei: case study of 67P/Churyumov-Gerasimenko. Astron. Astrophys. **630**, A5 (2019)

A. Johansen, A.N.Y.M.-M. Mac Low, Particle clumping and planetesimal formation depend strongly on metallicity. Astrophys. J. **704**, L75–L79 (2009)

A. Johansen, J.S. Oishi, M.-M. Mac Low, H. Klahr, T. Henning, A. Youdin, Rapid planetesimal formation in turbulent circumstellar disks. Nature **448**, 1022–1025 (2007)

A. Johansen, J. Blum, H. Tanaka, C. Ormel, M. Bizzarro, H. Rickman, The multifaceted planetesimal formation process, in *Protostars and Planets VI* (2014), pp. 547–570

A. Johansen, M.-M. Mac Low, P. Lacerda, M. Bizzarro, Growth of asteroids, planetary embryos, and Kuiper belt objects by chondrule accretion. Sci. Adv. **1**, e1500109 (2015)

R.E. Johnson, Irradiation effects in a comet's outer layers. J. Geophys. Res. **96**, 17553–17557 (1991)

G. Jones, M.M. Knight, K. Battams, . co-athors, The science of sungrazers, sunskirters, and other near-Sun comets. Space Sci. Rev. **214**(1), 20 (2018)

L. Jorda, R. Gaskell, C. Capanna, S. Hviid, P. Lamy, J. Durech, G. Faury, O. Groussin, P. Gutierrez, C. Jackman, S.J. Keihm, H.U. Keller, J. Knollenberg, E. Kührt, S. Marchi, S. Mottola, E. Palmer, F.P. Schloerb, H. Sierks, J.-B. Vincent, M.F. A'Hearn, C. Barbieri, R. Rodrigo, D. Koschny, H. Rickman, M.A. Barucci, J.L. Bertaux, I. Bertini, G. Cremonese, V.D. Deppo, B. Davidsson, S. Debei, M. De Cecco, S. Fornasier, M.F.A.C. Güttler, W.-H. Ip, J.R. Kramm, M.K. an, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, G. Naletto, N. Oklay, N. Thomas, C. Tubiana, K.-P. Wenzel, The global shape, density and rotation of comet 67P/Churyumov-Gerasimenko from preperihelion Rosetta/OSIRIS observations. Icarus **277**, 257–278 (2016)

M. Jutzi, E. Asphaug, The shape and structure of cometary nuclei as a result of low-velocity accretion. Science **348**(6241), 1355–1358 (2015)

M. Jutzi, W. Benz, Formation of bi-lobed shapes by sub-catastrophic collisions. A late origin of comet 67P's structure. Astron. Astrophys. **597**, A62 (2017)

M. Jutzi, W. Benz, A. Toliou, A. Morbidelli, R. Brasser, How primordial is the structure of comet 67P? Combined collisional and dynamical models suggest a late formation. Astron. Astrophys. **597**, A61 (2017)

H.U. Keller, D. Britt, B.J. Buratti, N. Thomas, In situ observations of cometary nuclei, in *Comets II*, ed. by M.C. Festou, U. Keller, H.A. Weaver (Univ. Arizona Press, Tucson, 2004), pp. 211–222

H.U. Keller, S. Mottola, B. Davidsson, . co-authors, Insolation, erosion and morphology of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **583**, A34 (2015)
M.S. Kelley, D.H. Wooden, The composition of dust in Jupiter-family comets inferred from infrared spectroscopy. Planet. Space Sci. **57**, 1133–1145 (2009)
S.J. Kenyon, J.X. Luu, Accretion in the early Kuiper belt. I. Coagulation and velocity evolution. Astron. J. **115**, 2136–2160 (1998)
D.J. Kessler, Derivation of the collision probability between orbiting objects: the lifetimes of Jupiter's outer moons. Icarus **48**, 39–48 (1981)
Y. Kim, M. Ishiguro, F. Usui, Physical properties of asteroids in comet-like orbits in infrared asteroid survey catalogs. Astrophys. J. **789**, 151 (2014)
M. Knight, M.F. A'Hearn, D.A. Biesecker, G. Faury, D.P. Hamilton, P. Lamy, A. Llebaria, Photometric study of the Kreutz comets observed by SOHO from 1996–2005. Astron. J. **139**, 926–949 (2010)
W. Kofman, A. Herique, Y. Barbin, J.-P. Barriot, V. Ciarletti, S. Clifford, P. Edenhofer, C. Elachi, C. Eyraud, J.-P. Goutail, E. Heggy, L. Jorda, J. Lasue, A.-C. Levasseur-Regourd, E. Nielsen, P. Pasquero, F. Preusker, P. Puget, D. Plettemeier, Y. Rogez, H. Sierks, C. Statz, H. Svedhem, I. Williams, S. Zine, J. Van Zyl, Properties of the 67P/Churyumov-Gerasimenko interior revealed by CONSERT radar. Science **249**, aab0639-1 (2015)
H. Kreutz, Investigations about the cometary system 1843 I, 1880 I and 1882 II Part I. Publ. Kiel Observatory. Printed by C. Schaidt, C.F. Mohr Nachfl. (1888)
M. Krolikówska, 67P/Churyumov-Gerasimenko—potential target for the Rosetta mission. Acta Astron. **54**, 195–209 (2003)
G.W. Kronk, *Comets, A Descriptive Catalog* (Enslow, Hillside, 1984). 331 pp
G.P. Kuiper, On the origin of the solar system, in *Astrophysics*, ed. by J.A. Hynek (McGraw Hill, New York, 1951), pp. 357–424
M. Küppers, H.U. Keller, E. Kührt, M.F. A'Hearn, K. Altwegg, R. Bertrand, H. Busemann, M.T. Capria, L. Colangeli, B. Davidsson, P. Ehrenfreund, J. Knollenberg, S. Mottola, A. Rathke, P. Weiss, M. Zolensky, E. Akim, A. Basilevsky, E. Galimov, M. Gerasimov, O. Korablev, I. Lomakin, M. Marov, M. Martynov, M. Nazarov, A. Zakharov, L. Zelenyi, A. Aronica, A.J. Ball, C. Barbieri, A. Bar-Nun, J. Benkhoff, J. Biele, N. Biver, J. Blum, D. Bockelée-Morvan, O. Botta, J.-H. Bredehöft, F. Capaccioni, S. Charnley, E. Cloutis, H. Cottin, G. Cremonese, J. Crovisier, S.A. Crowther, E.M. Epifani, F. Esposito, A.C. Ferrari, F. Ferri, M. Fulle, J. Gilmour, F. Goesmann, N. Gortsas, S.F. Green, O. Groussin, E. Grün, P.J. Gutiérrez, P. Hartogh, T. Henkel, M. Hilchenbach, T.-M. Ho, G. Horneck, S.F. Hviid, W.-H. Ip, A. Jäckel, E. Jessberger, R. Kallenbach, G. Kargl, N.I. Kömle, A. Korth, K. Kossacki, C. Krause, H. Krüger, Z.-Y. Li, J. Licandro, J.J. Lopez-Moreno, S.C. Lowry, I. Lyon, G. Magni, U. Mall, I. Mann, W. Markiewicz, Z. Martins, M. Maurette, U. Meierhenrich, V. Mennella, T.C. Ng, L.R. Nittler, P. Palumbo, M. Pätzold, D. Prialnik, M. Rengel, H. Rickman, J. Rodriguez, R. Roll, D. Rost, A. Rotundi, S. Sandford, M. Schönbächler, H. Sierks, R. Srama, R.M. Stroud, S. Szutowicz, C. Tornow, S. Ulamec, M. Wallis, W. Waniak, P. Weissman, R. Wieler, P. Wurz, K.L. Yung, J.C. Zarnecki, Triple F—a comet nucleus sample return mission. Exp. Astron. **23**, 809–847 (2009)
P.L. Lamy, I. Toth, Y.R. Fernández, H.A. Weaver, The sizes, shapes albedos, and colors of cometary nuclei, in *Comets II*, ed. by M.C. Festoru, H.U. Keller, H.A. Weaver (Univ. Arizona Press, Tucson, 2004), pp. 223–264
J. Lasue, R. Botet, A.C. Levasseur-Regourd, E. Hadamcik, Cometary nuclei internal structure from early aggregation simulations. Icarus **203**, 599–609 (2009)
J. Lasue, R. Botet, A.C. Levasseur-Regourd, E. Hadamcik, W. Kofman, Appearance of layered structures in numerical simulations of polydisperse bodies accretion: application to comet nuclei. Icarus **213**, 369–381 (2011)
A.-C. Levasseur-Regourd et al., Cometary dust. Space Sci. Rev. **214**, 64 (2018)
H.F. Levison, M.J. Duncan, From the Kuiper belt to Jupiter-family comets: the spatial distribution of ecliptic comets. Icarus **127**, 13–32 (1997)
H.F. Levison, M.J. Duncan, K. Zahnle, M. Holman, L. Dones, Planetary impact rates from ecliptic comets. Icarus **143**, 415–420 (2000)
D.R. Lide (ed.), *CRC Handbook of Chemistry and Physics*, 85th edn. (CRC Press, Boca Raton, 2004), pp. 6–8. ISBN 978-0-8493-0485-9
Z.Y. Lin, et al., Investigating the physical properties of outbursts on comet 67P/Churyumov-Gerasimenko. Mon. Not. R. Astron. Soc. **469**, S731–S740 (2017)
Y. Liu, T. Henning, C. Carrasco-González, C.J. Chandler, H. Linz, T. Birnstiel, R. van Boekel, L.M. Pérez, M. Flock, L. Testi, L.F. Rodríguez, R. Galván-Madrid, The properties of the inner disk around HL Tau: multi-wavelength modeling of the dust emission. Astron. Astrophys. **607**, A74 (2017)
S. Lorek, P. Lacerda, J. Blum, Local growth of dust- and ice-mixed aggregates as cometary building blocks in the solar nebula. Astron. Astrophys. **611**, A18 (2018)

S. Lowry, S.R. Duddy, B. Rozitis, S.F. Green, A. Fitzsimmons, C. Snodgrass, H. Hsieh, O. Hainaut, The nucleus of Comet 67P/Churyumov-Gerasimenko. A new shape model and thermophysical analysis. Astron. Astrophys. **548**, A12, 15pp (2012)

T. Mannel, M.S. Bentley, R. Schmied, H. Jeszenszky, A.C. Levasseur-Regourd, J. Romstedt, K. Torkar, Fractal cometary dust—a window into the early Solar system. Mon. Not. R. Astron. Soc. **462**, S304–S311 (2016)

T. Mannel, M.S. Bentley, P.D. Boakes, H. Jeszenszky, P. Ehrenfreund, C. Engrand, C. Koeberl, A.C. Levasseur-Regourd, J. Romstedt, R. Schmied, K. Torkar, I. Weber, Dust of comet 67P/Churyumov-Gerasimenko collected by Rosetta/MIDAS: classification and extension to the nanometre scale. Mon. Not. R. Astron. Soc. **630**, A26 (2019)

B.G. Marsden, The sungrazing comet group. Astron. J. **72**, 1170–1183 (1967)

B.G. Marsden, The sungrazing comet group. II. Astron. J. **98**, 2306–2321 (1989)

M. Massironi, E. Simoni, F. Marzari, et al., Two independent and primitive envelopes of the bilobate nucleus of comet 67P. Nature **526**, 402–405 (2015)

C. Matonti, N. Attree, O. Groussin, et al., Bilobate comet morphology and internal structure controlled by shear deformation. Nat. Geosci. **12**, 157–162 (2019)

J.A.M. McDonnell, P.L. Lamy, G.S.A. Pankiewucz, S.F. Green, C.H. Perry, The comet nucleus: Ice and dust morphological balancesin a production surface of comet P/Halley. LPSC **20**, 658 (1989)

K.J. Meech, O.R. Hainaut, B.G. Marsden, Comet nucleus size distributions from HST and Keck telescopes. Icarus **170**, 463–491 (2004)

H.J. Melosh, *Impact Cratering: A Geologic Process*. Oxford Monographs on Geology and Geophysics, vol. 11 (Oxford University Press, New York, 1989). 253 pp

E. Merenyi, L. Földy, K. Szegö, I. Toth, A. Kondor, The landscape of comet Halley. Icarus **86**, 9–20 (1990)

R. Merk, D. Prialnik, Early thermal and structural evolution of small bodies in the trans-Neptunian zone. Earth Moon Planets **92**, 359–374 (2003)

R. Merk, D. Prialnik, Combined modeling of thermal evolution and accretion of trans-neptunian objects—occurrence of high temperatures and liquid water. Icarus **183**, 283–295 (2006)

S. Merouane, B. Zaprudin, O. Stenzel, . co-auhtos, Dust particle flux and size distribution in the coma of 67P/Churyumov-Gerasimenko measured in situ by the COSIMA instrument on board Rosetta. Astron. Astrophys. **596**, A87 (2016)

D.J. Michels, N.R. Sheeley, R.A. Howard, M.J. Koomen, Observations of a comet on collision course with the Sun. Science **215**, 1097–1102 (1982)

M. Min, C.P. Dulllemond, M. Kama, C. Dominik, The thermal structure and the location of the snow line in the protosolar nebula: axisymmetric models with full 3-D radiative transfer. Icarus **212**, 416–426 (2011)

T. Montmerle, J.-C. Augereau, M. Chaussidon, M. Gounelle, B. Marty, A. Morbidelli, 3. Solar system formation and early evolution: the first 100 million years. Earth Moon Planets **98**, 39–95 (2006)

A. Morbidelli, H. Rickman, Comets as collisional fragments of a primordial planetesimal disk. Astron. Astrophys. **583**, A43 (2015)

T. Nakamura, T. Noguchi, A. Tsuchiyama, T. Ushikubo, N.T. Kita, J.W. Valley, M.E. Zolensky, Y. Kakazu, K. Sakamoto, E. Mashio, K. Uesugi, T. Nakano, Chondrule-like objects in short-period comet 81P/Wild 2. Science **321**, 664–667 (2008)

A. Natta, L. Testi, N. Calvet, T. Henning, R. Waters, D. Wilner, Dust in protoplanetary disks: properties and evolution, in *Protostars and Planets V* (2007), pp. 767–781

D. Nesvorný, Jumping Neptune can explain the Kuiper belt kernel. Astron. J. **150**, 68 (2015a)

D. Nesvorný, Evidence for slow migration of Neptune from the inclination distribution of Kuiper belt objects. Astron. J. **150**, 73 (2015b)

D. Nesvorný, A. Morbidelli, Statistical study of the early solar system's instability with four, five, and six giant planets. Astron. J. **144**, 117 (2012)

D. Nesvorný, D. Vokrouhlický, Chaotic capture of Neptune Trojans. Astron. J. **137**, 5003–5011 (2009)

D. Nesvorný, D. Vokrouhlický, Neptune's orbital migration was grainy, not smooth. Astrophys. J. **825**, 94 (2016)

D. Nesvorný, D. Vokrouhlický, A. Morbidelli, Capture of irregular satellites during planetary encounters. Astron. J. **133**, 1962–1976 (2007)

D. Nesvorný, A.N. Youdin, D.C. Richardson, Formation of Kuiper belt binaries by gravitational collapse. Astron. J. **140**, 785–793 (2010)

D. Nesvorný, D. Vokrouhlický, A. Morbidelli, Capture of Trojans by jumping Jupiter. Astrophys. J. **768**, 45 (2013)

D. Nesvorný, D. Vokrouhlický, L. Dones, H.F. Levison, N. Kaib, A. Morbidelli, Origin and evolution of short-period comets. Astrophys. J. **845**, 27 (2017)

T.L. Norris, A.J. Gancarz, D.J. Rokop, K.W. Thomas, Half like of Al-26. J. Geophys. Res. **88**, B331–B333 (1983)

J. Oberst, B. Giese, E. Howington-Kraus, R. Kirk, L. Soderblom, B. Buratti, M. Hicks, R. Nelson, D. Britt, The nucleus of comet Borrelly: a study of morphology and surface brightness. Icarus **167**, 70–79 (2004)

D.P. O'Brien, R. Greenberg, The collisional and dynamical evolution of the main-belt and NEA size distributions. Icarus **178**, 179–212 (2005)

C.R. O'Dell, A new model for cometary nuclei. Icarus **19**, 137–146 (1971)

R.C. Ogliore, G.R. Huss, N. Nagashima, A.L. Butterworth, Z. Gainsforth, J. Stodolna, A.J. Westphal, D. Joswiak, T. Tyliszczak, Incorporation of a late-forming chondrule into comet Wild 2. Astrophys. J. Lett. **745**, L19 (2012)

N. Oklay, J.-B. Vincent, S. Fornasier, M. Pajola, S. Besse, B.J.R. Davidsson, L.M. Lara, S. Mottola, G. Naletto, H. Sierks, A.M. Barucci, F. Scholten, F. Preusker, A. Pommerol, N. Masoumzadeh, M. Lazzarin, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, M.F. A'Hearn, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, M. Fulle, O. Groussin, P.J. Gutierrez, C. Güttler, I. Hall, M. Hofmann, S.F. Hviid, W.-H. Ip, L. Jorda, H.U. Keller, J. Knollenberg, G. Kovacs, J.-R. Kramm, E. Kührt, M. Küppers, Z.-Y. Lin, F. Marzari, F. Moreno, X. Shi, N. Thomas, I. Toth, C. Tubiana, Variegation on comet 67P/Churyumov-Gerasimenko in the regions showing activity. Astron. Astrophys. **586**, A80 (2016)

J.H. Oort, The structure of the cloud of comets surrounding the solar system and a hypothesis concerning its origin. Bull. Astron. Inst. Neth. **11**, 91–110 (1950)

E.J. Öpik, Collision probabilities with the planets and the distribution of interplanetary matter. Proc. R. Ir. Acad. A **54**, 165–199 (1951)

T. Ott, E. Drolshagen, D. Koschny, C. Güttler, C. Tubiana, E. Frattin, J. Agarwal, H. Sierks, I. Bertini, C. Barbieri, P.I. Lamy, R. Rodrigo, H. Rickman, M.F. A'Hearn, M.A. Barucci, J.-L. Bertaux, S. Boudreault, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, J. Deller, C. Feller, S. Fornasier, M. Fulle, B. Geiger, A. Gicquel, O. Groussin, P.J. Gutiérrez, M. Hofmann, S.F. Hviid, W.-H. Ip, L. Jorda, H.U. Keller, J. Knollenberg, G. Kovacs, J.R. Kramm, E. Kührt, M. Küppers, L.M. Lara, M. Lazzarin, Z.-Y. Lin, J.J. López-Moreno, F. Marzari, S. Mottola, G. Naletto, N. Oklay, M. Pajola, X. Shi, N. Thomas, J.-B. Vincent, B. Poppe, Dust mass distribution around comet 67P/Churyumov-Gerasimenko determined via parallax measurements using Rosetta's OSIRIS cameras. Mon. Not. R. Astron. Soc. **469**, S276–S284 (2017)

M. Pätzold, T. Andert, M. Hahn, S.W. Asmar, J.-P. Barriot, M.K. Bird, B. Häusler, K. Peter, S. Tellmann, E. Grün, P.R. Weissman, H. Sierks, L. Jorda, R. Gaskell, F. Preusker, F. Scholten, A homogeneous nucleus for comet 67P/Churyumov-Gerasimenko from its gravity field. Nature **530**, 63–65 (2016)

M. Pätzold, T. Andert, J.-P. Barriot, M. Hahn, M. Bird, B. Häusler, S.A. Tellemann, The mass loss of comet 67P/Churyumov-Gerasimenko. AAS/DPS Meet. **49**, 509.01 (2017)

L. Penasa, M. Massironi, G. Naletto, E. Simioni, S. Ferrari, M. Pajola, A. Lucchetti, F. Preusker, F. Scholten, L. Jorda, R. Gaskell, F. Ferri, F. Marzari, B. Davidsson, S. Mottola, H. Sierks, C. Barbieri, P.L. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.F. A'Hearn, M.A. Barucci, J.L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, S. Debei, M. De Cecco, J. Deller, C. Feller, S. Fornasier, E. Frattin, M. Fulle, O. Groussin, P.J. Gutierrez, C. Guttler, M. Hofmann, S.F. Hviid, W.H. Ip, J. Knollenberg, J.R. Kramm, E. Kuhrt, M. Kuppers, F. La Forgia, L.M. Lara, M. Lazzarin, J.-C. Lee, J.J. Lopez Moreno, N. Oklay, X. Shi, N. Thomas, C. Tubiana, J.B. Vincent, A threedimensional modelling of the layered structure of comet 67P/Churyumov-Gerasimenko. Mon. Not. R. Astron. Soc. **469**, S741–S754 (2017)

L.M. Pérez, J.M. Carpenter, C.J. Chandler, A. Isella, S.M. Andrews, L. Ricci, N. Calvet, S.A. Corder, A.T. Deller, C.P. Dullemond, J.S. Greaves, R.J. Harris, T. Henning, W. Kwon, J. Lazio, H. Linz, L.G. Mundy, A.I. Sargent, S. Storm, L. Testi, D.J. Wilner, Constraints on the radial variation of grain growth in the AS 209 circumstellar disk. Astrophys. J. Lett. **760**, L17 (2012)

L.M. Pérez, C.J. Chandler, A. Isella, J.M. Carpenter, S.M. Andrews, N. Calvet, S.A. Corder, A.T. Deller, C.P. Dullemond, J.S. Greaves, R.J. Harris, T. Henning, W. Kwon, J. Lazio, H. Linz, L.G. Mundy, L. Ricci, A.I. Sargent, S. Storm, M. Tazzari, L. Testi, D.J. Wilner, Grain growth in the circumstellar disks of the young stars CY Tau and DoAr 25. Astrophys. J. **813**, 41 (2015)

M. Podolak, D. Prialnik, The conditions for liquid water in cometary nuclei, in *Comets and the Origin and Evolution of Life*, ed. by P.J. Thomas, C. Chyba, C. McKay (Springer, Berlin, 2006)

F. Poulet, A. Lucchetti, J.-P. Bibring, J. Carter, B. Gondet, L. Jorda, Y. Langevin, C. Pilorget, C. Capanna, G. Cremonese, Origin of the local structures at the Philae landing site and possible implications on the formation and evolution of 67P/Churyumov-Gerasimenko. Mon. Not. R. Astron. Soc. **462**, S23–S32 (2016)

F. Preusker, F. Scholten, K.-D. Matz, T. Roatsch, K. Willner, S.F. Hviid, J. Knollenberg, L. Jorda, P.J. Gutiérrez, E. Kührt, S. Mottola, M.F. A'Hearn, N. Thomas, H. Sierks, C. Barbieri, P. Lamy, R. Rodrigo, D. Koschny, H. Rickman, H.U. Keller, J. Agarwal, M.A. Barucci, J.-L. Bertaux, I. Bertini, G. Cremonese, V. Da Deppo, B. Davidsson, S. Debei, M. De Cecco, S. Fornasier, M. Fulle, O. Groussin,

C. Güttler, W.-H. Ip, J.R. Kramm, M. Küppers, L.M. Lara, M. Lazzarin, J.J. Lopez Moreno, F. Marzari, H. Michalik, G. Naletto, N. Oklay, C. Tubiana, J.-B. Vincent, Shape model, reference system definition, and cartographic mapping standards for comet 67P/Churyumov-Gerasimenko—Stereo-photogrammetric analysis of Rosetta/OSIRIS image data. Astron. Astrophys. **583**, A33 (2015)

F. Preusker, F. Scholten, K.-D. Matz, et al., The global meter-level shape model of comet 67P/Churyumov-Gerasimenko. Astron. Astrophys. **607**, L1 (2017)

D. Prialnik, M. Podolak, Radioactive heating of porous comet nuclei. Icarus **117**, 420–430 (1995)

D. Prialnik, M. Podolak, Changes in the structure of comet nuclei due to radioactive heating. Space Sci. Rev. **90**, 169–178 (1999)

D. Prialnik, A. Bar-Nun, M. Podolak, Radiogenic heating of comets by ^{26}Al and implications for their time of formation. Astrophys. J. **319**, 993–1002 (1987)

L. Ricci, L. Testi, A. Natta, K.J. Brooks, Dust grain growth in ρ-Ophiuchi protoplanetary disks. Astron. Astrophys. **521**, A66 (2010)

J.E. Richardson, H.J. Melosh, C.M. Lisse, B. Carcich, A ballistics analysis of the Deep Impact ejecta plume: determining comet Tempel 1's gravity, mass, and density. Icarus **190**(2), 357–390 (2007)

H. Rickman, Masses and densities of Comets Halley and Kopff, in *The Comet Nucleus Sample Return Mission*, ed. by O. Melita (ESA Publications Division, ESTEC, Noordwijk, 1986), pp. 195–205

H. Rickman, The thermal history and structure of cometary nuclei, in *Comets in the Post-Halley Era*, vol. 2, ed. by R.L. Newburn, M. Neugebauer, J. Rahe (Kluwer Academic Publishers, Dordrecht, 1991), pp. 733–760

H. Rickman, L. Kamel, M.C. Festou, C. Froeschle, Estimates of masses, volumes and densities of short-period comet nuclei, in *Symposium on the Diversity and Similarity of Comets*, ed. by E.J. Rolfe, B. Battrick (ESA Publications Division, ESTEC, Noordwijk, 1987), pp. 471–481

S.J. Robbins et al., Craters of the Pluto-Charon system. Icarus **287**, 187–206 (2017)

K. Ros, A. Johansen, Ice condensation as a planet formation mechanism. Astrophys. J. **552**, A113 (2013)

A. Rotundi, H. Sierks, V. Della Corte, . co-authors, Dust measurements in the coma of comet 67P/Churyumov-Gerasimenko inbound to the Sun. Science **347**, aaa3905-06 (2015)

D.D. Sasselov, M. Lecar, On the snow line in dusty protoplanetary disks. Astrophys. J. **528**, 995–998 (2000)

U. Schäfer, C.-C. Yang, A. Johansen, Initil mass function of planetesimals formed by the streaming instability. Astron. Astrophys. **597**, A69 (2017)

R. Schräpler, J. Blum, S. Krijt, J.-H. Raabe, The physics of protoplanetary dust agglomerates. X. High-velocity collisions between small and large dust agglomerates as a growth barrier. Astrophys. J. **853**, 74 (2018)

S.R. Schwartz, P. Michel, M. Jutzi, S. Marchi, Y. Zhang, D.C. Richardson, Catastrophic disruptions as the origin of bilobate comets. Nat. Astron. **2**, 379–382 (2018)

R. Seu, R.J. Phillips, D. Biccari, R. Orosei, A. Masadea, G. Pcardi, A. Safaenilli, B.A. Campbell, J.J. Plaut, L. Marinangeli, S.E. Smrekar, D.C. Nunes, SHARAD sounding radar on the Mars Reconnaissance Orbiter. J. Geophys. Res., Planets **112**(E5), Issue (2007)

N.R. Sheeley Jr., R.A. Howard, M.J. Koomen, D.J. Michels, Coronoagraphic observations of two new sun-grazing comets. Nature **300**, 239–242 (1982)

C.S. Shoemaker, E.M. Shoemaker, D. Levy (1993). IAU Circular 5725

E.M. Shoemaker, P.R. Weissman, C.S. Shoemaker, The flux of periodic comets near Earth, in *Hazards Due to Comets and Asteroids*, ed. by T. Gehrels (University of Arizona Press, Tucson, 1995), pp. 313–335

A. Sicilia-Aguilar, L. Hartmann, N. Calvet, S.T. Megeath, J. Muzerolle, L. Allen, P. D'Alessio, B. Merlin, J. Stauffer, E. Young, C. Lada, Disk evolution in CEP OB2: results from the Spitzer Space Telescope. Astrophys. J. **638**, 897–919 (2006)

H. Sierks, et al., On the nucleus structure and activity of comet 67P/Churyumov-Gerasimenko. Science **347**, aa1043 (2015)

J.B. Simon, P.J. Armitage, R. Li, A.N. Youdin, The mass and size distribution of planetesimals formed by the streaming instability. I. The role of self-gravity. Astrophys. J. **822**, 55 (2016)

Y. Skorov, J. Blum, Dust release and tensile strength of the non-volatile layer of cometary nuclei. Icarus **221**, 1–11 (2012)

C. Snodgrass, A. Fitzsimmons, S.C. Lowry, P. Weissman, The size distribution of Jupiter family comets. Mon. Not. R. Astron. Soc. **414**, 458–469 (2011)

L.A. Soderblom, T.L. Becker, G. Bennett, D.C. Boice, D.T. Britt, R.H. Brown, B.J. Buratti, C. Isbell, B. Giese, T. Hare, M.D. Hicks, E. Howington-Kraus, R.L. Kirk, M. Lee, R.M. Nelson, J. Oberst, T.C. Owen, M.D. Rayman, B.R. Sandel, S.A. Stern, N. Thomas, R.V. Yelle, Observations of Comet 19P/Borrelly by the Miniature Integrated Camera and Spectrometer aboard Deep Space 1. Science **296**, 1087–1091 (2002)

A. Sosa, J.A. Fernández, Cometary masses derived from non-gravitational forces. Mon. Not. R. Astron. Soc. **393**, 192–214 (2009)

D.C. Stephens, K.S. Noll, Detection of six trans-neptunian binaries with NICMOS: a high fraction of binaries in the cold classical disk. Astron. J. **131**, 1142–1148 (2006)
S.A. Stern, The effects of mechanical interaction between the interstellar medium and comets. Icarus **68**, 276–283 (1986)
S.A. Stern, Two important mechanisms contributing to cometary evolution in the Oort cloud. LPSC **18**, 951 (1987). (Abstract)
S.A. Stern, P.R. Weissman, Rapid collisional evolution of comets during the formation of the Oort cloud. Nature **409**, 589–591 (2001)
G. Strazzulla, Ion irradiation and the origin of cometary materials. Space Sci. Rev. **90**, 269–274 (1999)
G. Tancredi, J.A. Fernández, H. Rickman, J. Licandro, Nuclear magnitudes and the size distribution of Jupiter family comets. Icarus **187**, 527–549 (2006)
M. Tazzari, L. Testi, B. Ercolano, A. Natta, A. Isella, C.J. Chandler, L.M. Pérez, S. Andrews, D.J. Wilner, L. Ricci, T. Henning, H. Linz, W. Kwon, S.A. Corder, C.P. Dullemond, J.M. Carpenter, A.I. Sargent, L. Mundy, S. Storm, N. Calvet, J.A. Greaves, J. Lazio, A.T. Deller, Multiwavelength analysis for interferometric (sub-)mm observations of protoplanetary disks. Radial constraints on the dust properties and the disk structure. Astron. Astrophys. **588**, A53 (2016)
L. Testi, T. Birnstiel, L. Ricci, S. Andrews, J. Blum, J. Carpenter, C. Dominik, A. Isella, A. Natta, J.P. Williams, D.J. Wilner, Dust evolution in protoplanetary disks, in *Protostars and Planets VI* (2014), pp. 339–361
P.C. Thomas, J. Veverka, M.J.S. Belton, A. Hidy, M.F. A'Hearn, T.L. Farnham, O. Groussin, J.-Y. Li, L.A. McFadden, J. Sunshine, D. Wellnitz, C. Lisse, P. Schultz, K.J. Meech, W.A. Delamere, The shape, topography, and geology of Tempel 1 from Deep Impact observations. Icarus **187**, 4–15 (2007)
N. Thomas, H. Sierks, C. Barbieri, . co-authors, The morphological diversity of comet 67P/Churyumov-Gerasimenko. Science **347**, aaa0440 (2015)
F. Trotta, L. Testi, A. Natta, A. Isella, L. Ricci, Constraints on the radial distribution of the dust properties in the CQ Tauri protoplanetary disk. Astron. Astrophys. **558**, A64 (2013)
K. Tsiganis, R. Gomes, A. Morbidelli, H.F. Levison, Origin of the orbital architecture of the giant planets of the solar system. Nature **435**, 459–461 (2005)
P.D. Tsou et al., Experiments on intact capture of hypervelocity particles. LPSC **15**, 866–867 (1984). (Abstract)
R. van Boekel, M. Min, C. Leinert, L.B.F.M. Waters, A. Richichi, O. Chesneau, C. Dominik, W. Jaffe, A. Dutrey, U. Graser, T. Henning, J. de Jong, R. Köhler, A. de Koter, B. Lopez, F. Malbet, S. Morel, F. Paresce, G. Perrin, T. Preibisch, F. Przygodda, M. Schöller, M. Wittkowski, The building blocks of planets within the 'terrestrial' region of protoplanetary disks. Nature **432**, 479–482 (2004)
J. Veverka, K. Klaasen, M. A'Hearn, . co-authors, Return to comet Tempel 1: overview of Stardust-NExT results. Icarus **222**, 424–435 (2013)
E. Vilenius, C. Kiss, T. Müller, M. Mommert, P. Santos-Sanz, A. Pal, J. Stansberry, M. Mueller, N. Peixinho, E. Lellouch, S. Fornasier, A. Delsanti, A. Thirouin, J.L. Ortiz, R. Duffard, D. Perna, F. Henry, "TNOs are cool": a survey of the trans-Neptunian region. X. Analysis of classical Kuiper belt objects from Herschel and Spitzer observations. Astron. Astrophys. **564**, A35 (2014)
J.-B. Vincent, D. Bodewits, S. Besse, . co-authors, Large heterogeneities in comet 67P as revealed by active pits from sinkhole collapse. Nature **523**, 63–68 (2015)
J.-B. Vincent, M.F. A'Hearn, Z.-Y. Lin, et al., Summer fireworks on comet 67P. Mon. Not. R. Astron. Soc. **462**, 184–194 (2016b)
J.-B. Vincent, N. Oklay, M. Pajola, . co-authors, Are fractured cliffs the source of cometary dust jets? Insights from OSIRIS/Rosetta at 67P/Churyumov-Gerasimenko. Astron. Astrophys. **587**, A14 (2016a)
K. Wada, H. Tanaka, T. Suyama, H. Kimura, T. Yamamoto, Numerical simulation of dust aggregate collisions. II. Compression and disruption of three-dimensional aggregates in head-on collisions. Astrophys. J. **677**, 1296–1308 (2008)
K. Wada, H. Tanaka, T. Suyama, H. Kimura, T. Yamamoto, Collisional growth conditions for dust aggregates. Astrophys. J. **702**, 1490–1501 (2009)
K. Wahlberg Jansson, A. Johansen, Formation of pebble-pile planetesimals. Astron. Astrophys. **570**, A47 (2014)
K. Wahlberg Jansson, A. Johansen, Radially resolved simulations of collapsing pebble clouds in protoplanetary discs. Mon. Not. R. Astron. Soc. **469**, S149–S157 (2017)
K. Wahlberg Jansson, A. Johansen, M. Bukhari Syed, J. Blum, The role of pebble fragmentation in planetesimal formation. II. Numerical simulations. Astrophys. J. **835**, 109 (2017)
H.A. Weaver, Not a rubble pile? Science **304**, 1760–1762 (2004)
H.A. Weaver, Z. Sekanina, I. Toth, . co-authors, HST and VLT investigations of the fragments of Comet C/1999 S4 (LINEAR). Science **292**, 1329–1334 (2001)

H.A. Weaver, C.M. Lisse, M.J. Mutchler, P. Lamy, I. Toth, W.T. Reach, Hubble Space Telescope investigation of the disintegration of 73P/Schwassmann-Wachmann 3. Bull. Am. Astron. Soc. **38**, 490 (2006)
S.J. Weidenschilling, Aerodynamics of solid bodies in the solar nebula. Mon. Not. R. Astron. Soc. **180**, 57–70 (1977)
S.J. Weidenschilling, The origin of comets in the solar nebula: a unifed model. Icarus **127**, 290–306 (1997)
R. Weidling, C. Güttler, J. Blum, F. Brauer, The physics of protoplanetesimal dust agglomerates. III. Compaction in multiple collisions. Astrophys. J. **696**, 2036–2043 (2009)
P.R. Weissman, Physical and dynamical evolution of long-period comets, in *Dynamics of the Solar System*, ed. by R.L. Duncombe (D. Reidel, Dordrecht, 1979), pp. 277–282
P.R. Weissman, Physical loss of long-period comets. Astron. Astrophys. **85**, 191–196 (1980)
P. Weissman, Cometary impacts on the terrestrial planets, in *Conference on Planetary Volatiles*. LPI Contribution, vol. 488 (1982), p. 109
P.R. Weissman, Cometary impacts with the Sun: physical and dynamical considerations. Icarus **55**, 448–454 (1983)
P.R. Weissman, Are cometary nuclei primordial rubble piles? Nature **320**, 242–244 (1986)
P.R. Weissman, Post-perihelion brightening of Halley's Comet: spring time for Halley. Astron. Astrophys. **187**(873), 878 (1987)
P.R. Weissman, in *Comet Halley, Investigations, Results, Interpretations*, vol. 2, ed. by J. Mason (1990), pp. 241–257
P.R. Weissman, S.C. Lowry, Structure and density of cometary nuclei. Meteorit. Planet. Sci. **43**, 1033–1047 (2008)
P.R. Weissman, W.F. Bottke, H.F. Levison, Evolution of comets into asteroids, in *Asteroids III*, ed. by W. Bottke, A. Cellino, P. Paolicchi, R. Binzel (Univ. Arizona Press, Tucson, 2002), pp. 669–686
P.R. Weissman, E. Asphaug, S.C. Lowry, Structure and density of cometary nuclei, in *Comets II*, ed. by M.C. Festou, U. Keller, H.A. Weaver (Univ. Arizona Press, Tucson, 2004), pp. 337–357
J.S. Wettlaufer, Accretion in protoplanetary disks by collisional fusion. Astrophys. J. **719**, 540–549 (2010)
F.L. Whipple, A comet model, I, the acceleration of comet Encke. Astrophys. J. **110**, 375–394 (1950)
F. Windmark, T. Birnstiel, C. Güttler, J. Blum, C.P. Dullemond, T. Henning, Planetesimal formation by sweep-up: how the bouncing barrier can be beneficial to growth. Astron. Astrophys. **540**, A73 (2012a)
F. Windmark, T. Birnstiel, C.W. Ormel, C.P. Dullemond, Breaking through: the effects of a velocity distribution on barriers to dust growth. Astron. Astrophys. **544**, L16 (2012b)
P. Wurz, M. Rubin, K. Altwegg, . co-authors, Solar wind sputtering from the surface of comet Churyumov-Gerasimenko. Astron. Astrophys. **583**, A22 (2015)
T. Yamamoto, Formation history and environment of cometary nuclei, in *Ices of the Solar System*, ed. by J. Klinger, D. Benest, A. Dollfus, R. Smoluchowski. NATO ASI Series C: Mathematical and Physical Sciences, vol. 156 (1985), pp. 205–219
C.-C. Yang, A. Johansen, D. Carrera, Concentrating small particles in protoplanetary disks through the streaming instability. Astron. Astrophys. **606**, A80 (2017)
A.N. Youdin, J. Goodman, Streaming instabilities in protoplanetary disks. Astrophys. J. **620**, 459–469 (2005)
A. Zsom, C.W. Ormel, C. Güttler, J. Blum, C.P. Dullemond, The outcome of protoplanetary dust growth: pebbles, boulders, or planetesimals? II. Introducing the bouncing barrier. Astron. Astrophys. **513**, A57 (2010)
B. Zuckerman, T. Foreille, J.H. Kastner, Inhibition of giant-planet formation by rapid gas depletion around young stars. Nature **373**, 494–496 (1995)