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Structure and density of cometary nuclei

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Abstract–Understanding the nature of the cometary nucleus remains one of the major problems in solar system science. Whipple's (1950) icy conglomerate model has been very successful at explaining a range of cometary phenomena, including the source of cometary activity and the nongravitational orbital motion of the nuclei. However, the internal structure of the nuclei is still largely unknown. We review herein the evidence for cometary nuclei as fluffy aggregates or primordial rubble piles, as first proposed by Donn et al. (1985) and Weissman (1986). These models assume that cometary nuclei are weakly bonded aggregations of smaller, icy-conglomerate planetesimals, possibly held together only by self-gravity. Evidence for this model comes from studies of the accretion and subsequent evolution of material in the solar nebula, from observations of disrupted comets, and in particular comet Shoemaker-Levy 9, from measurements of the ensemble rotational properties of observed cometary nuclei, and from recent spacecraft missions to comets. Although the evidence for rubble pile nuclei is growing, the eventual answer to this question will likely not come until we can place a spacecraft in orbit around a cometary nucleus and study it in detail over many months to years. ESA's Rosetta mission, now en route to comet 67P/Churyumov-Gerasimenko, will provide that opportunity.

INTRODUCTION

Cometary nuclei are among the least understood bodies in the solar system. Although Whipple's (1950) icy-conglomerate model was dramatically and unequivocally confirmed by the spacecraft flybys of the nucleus of comet Halley in 1986, the internal structure and density of the nucleus remains largely a mystery. Nevertheless, progress has been made and there is increasing evidence to support the concept that cometary nuclei are fluffy aggregates (Donn and Hughes 1986) or primordial rubble piles (Weissman 1986). These models require that cometary nuclei are underdense, probably at both microscopic and macroscopic scales.

Additional spacecraft encounters with comets have now revealed a total of four nuclei to us: 1P/Halley in 1986 by Giotto and Vega (Keller et al. 1986; Sagdeev et al. 1986), 19P/Borrelly in 2001 by Deep Space 1 (Soderblom et al. 2001), 81P/Wild 2 in 2004 by Stardust (Brownlee et al. 2004), and 9P/Tempel 1 in 2005 by Deep Impact (A'Hearn et al. 2005). Images of the four nuclei are shown in Fig. 1. The spacecraft imaging has revealed that these are a diverse collection of bodies with substantial differences in both shape and surface topography. The reasons for this diversity are not known, but could include different formation zones in the solar nebula, different collisional histories before dynamically evolving to small perihelia, the number (and type) of orbits the nuclei have occupied as active comets with perihelia less than 3 AU, and the physical evolution of their surfaces over time.

This paper will examine the proposed models for the structure and density of cometary nuclei and will review the increasing body of evidence that supports low density models. In the Models of Comet Nucleus Structure section, we discuss the proposed models for the internal structure of cometary nuclei. The recent evidence supporting those models is described in the Evidence Supporting the Fluffy Aggregate and Rubble Pile Models section. A discussion of the methods used to estimate the density of cometary nuclei is provided in the Density of Cometary Nuclei section. In the Results from Spacecraft Encounters section, we discuss what has been learned from the comets encountered by spacecraft missions.

MODELS OF COMET NUCLEUS STRUCTURE

Whipple's original papers (1950, 1951, 1955) described the cometary nucleus as a solid body composed of a mix of

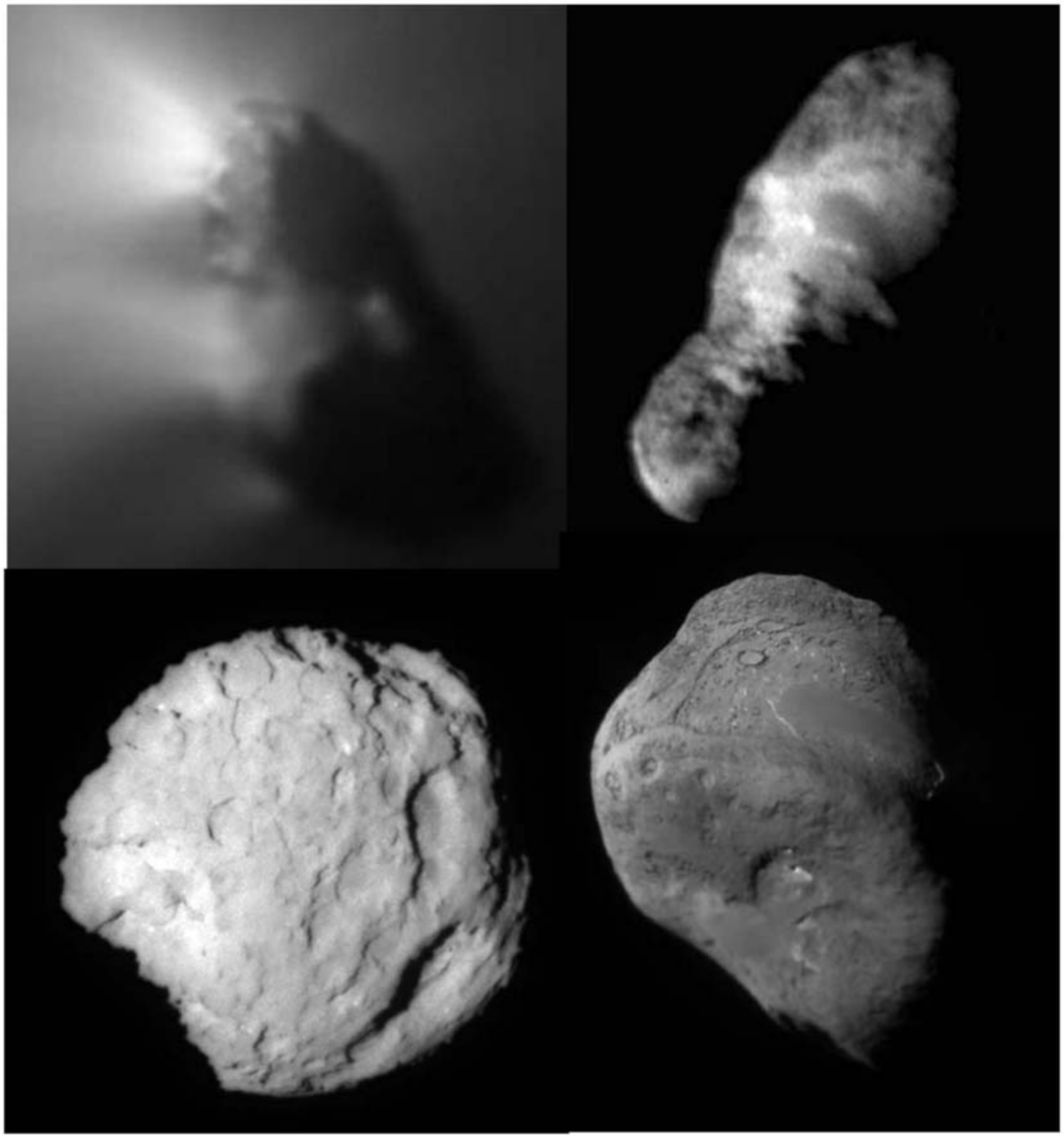

Fig. 1. The four cometary nuclei imaged by flyby spacecraft to date. Top left: 1P/Halley by Giotto in 1986; top right: 19P/Borrelly by Deep Space 1 in 2001; bottom left: 81P/Wild 2 by Stardust in 2004; and bottom right: 9P/Tempel 1 by Deep Impact in 2005. The nuclei show substantial differences in shape and surface morphology. The images are not shown to scale. The Halley nucleus is ~15.3 × 7.2 km in diameter; the Borrelly nucleus is ~8.0 × 3.2 km; the Wild 2 nucleus is ~5.5 × 4.0 km; and the Tempel 1 nucleus is 7.6 × 4.9 km.

volatile ices and meteoritic materials. Whipple showed that this model could explain a number of features of comets, in particular the nongravitational forces that were needed to account for the irregular return times of numerous periodic comets. Whipple's seminal work laid the groundwork for much of the future progress in understanding cometary nuclei and cometary phenomena. However, Whipple never addressed the internal structure of cometary nuclei.

The approach of comet Halley in 1986 stimulated new efforts that attempted to predict how the nucleus of the comet would appear. At that time, spacecraft had not encountered any comets or asteroids, and the closest observed analog was the two Martian moons, Phobos and Deimos, which had been imaged by the Mariner 9 and Viking missions orbiting Mars. The three most prominent models suggested at that time were the "fluffy aggregate" model of Donn et al. (1985) and Donn and Hughes (1986), the "primordial rubble pile" of Weissman (1986), and the "icy-glue" model of Gombosi and Houpis (1986). These models are illustrated in Fig. 2.

The primary concept in both the Donn et al. (1985) and Weissman (1986) models, both proposed prior to the Halley spacecraft encounters, was that cometary nuclei were weakly bonded aggregates of smaller icy planetesimals (which we will refer to as cometesimals), brought together at low velocity in a random fashion. With little in the way of modifying processes or energy sources available to change this initial structure, the cometary nuclei would preserve their highly irregular initial shapes and very porous, easily

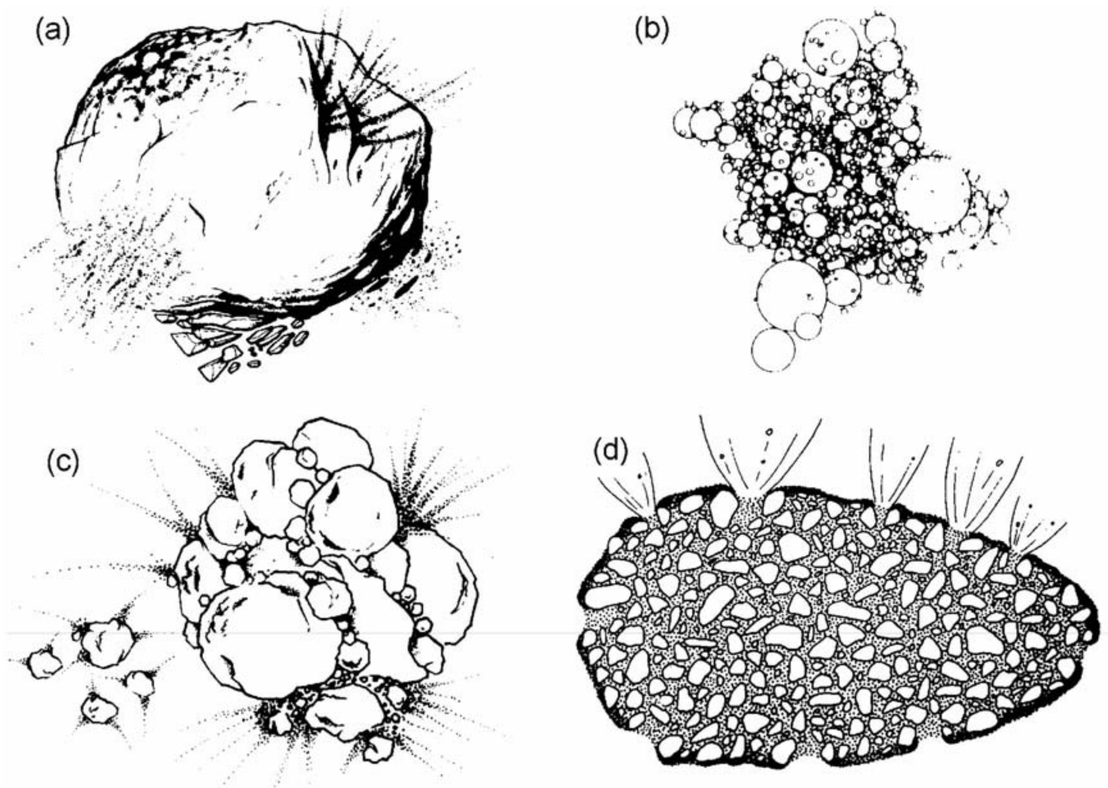

Fig. 2. Artists' concepts of proposed models for cometary nuclei: a) Whipple's icy conglomerate model as envisioned by Weissman and Kieffer (1981); b) the fluffy aggregate model of Donn et al. (1985); c) the primordial rubble pile model of Weissman (1986); and d) the icy-glue model of Gombosi and Houpis (1986). All but (d) were proposed prior to the spacecraft flybys of comet 1P/Halley in 1986. Whipple's seminal papers in the 1950s did not address the interior structure of the nucleus.

fragmented structure over the history of the solar system. The fact that cometary nuclei spent most of their lifetimes in "cold storage" in the Oort cloud and Kuiper belt contributed further to the expectation that they would be unprocessed, primitive bodies.

Donn and colleagues' arguments came from their studies of the accretion of small grains in the solar nebula, realizing that random accretion would lead to self-similar structures at larger spatial scales. Weissman, on the other hand, showed in a calculation that the total gravitational potential energy of a typical cometary nucleus, say 5 km in radius, was not sufficient to raise the temperature of the resulting nucleus by even one degree Kelvin during the accretion process, and thus there was no energy source to mold the nucleus into a single, monolithic body. Both Donn et al. and Weissman suggested that a fragmentary structure for cometary nuclei could help to explain such observed phenomena as outbursts and splitting, and could provide a mechanism for irregular activity on the surfaces of cometary nuclei.

Weissman drew analogies with previous work on the rubble pile structure of asteroids by Davis et al. (1979). However, he appended the term "primordial" to suggest that the nuclei were original solar nebula material, and not the products of earlier, disrupted bodies. We now recognize that collisional evolution has almost certainly played a role for cometary nuclei also (Stern 1995, 1996; Farinella and Davis 1996; Stern and Weissman 2001; Charnoz and Morbidelli 2007), both in the Kuiper belt and during the ejection of icy planetesimals from the giant planets zone to the Oort cloud. Thus, nuclei may indeed be reassembled rubble piles from earlier generations of icy planetesimals. This could include mixing of cometesimals formed in different regions of the giant planets zone or the Kuiper belt, and thus reflect different compositions and thermal environments. This then provides a natural explanation for the compositional heterogeneity seen in some comets and in the returned Stardust samples (McKeegan et al. 2006). However, the full implications of this collisional history for the primitive nature of cometary materials have yet to be explored.

The Gombosi and Houpis (1986) icy-glue model, proposed after the Halley spacecraft flybys, suggested that comets were composed of porous refractory boulders with compositions similar to carbonaceous asteroids, cemented together by an icy-conglomerate glue. In the icy-glue model the refractory boulders provided the irregular topography seen in the Giotto and Vega images of the Halley nucleus (Keller et al. 1986; Sagdeev et al. 1986) and also helped to explain the collimated jets seen emanating from the surface (from active icy-glue regions between pairs of non-volatile boulders). Although it contains some interesting features, the icy-glue model has not received wide support because there is no evidence for a population of remnant refractory "boulders" from decaying comets. Also, it could not explain many of the features of the breakup of comet Shoemaker-Levy 9 (D/1993 F2, see below).

Recently, Belton et al. (2007) have suggested a layered model for cometary nuclei, where individual cometesimals strike the accreting nucleus gently during the formation process in the protosolar nebula, and then collapse into thin layers because of the low strength of the materials. They call this model "talps," which is the word "splat" spelled backwards. Belton et al. cite as evidence the apparent layers seen on comet Tempel 1 in images taken by the Deep Impact spacecraft (A'Hearn et al. 2005), which they interpret as primordial rather than evolutionary. However, Belton et al. (2007) also recognize that this layered terrain could not survive if the nuclei undergo disruptive collisional processing at some time in their histories. As noted above, theoretical modeling shows that all comets experience a severe collisional period early in their histories. This includes the Kuiper belt, the Scattered disk, and the Oort cloud comets. Thus, we conclude that at present the "splat" model is not a viable explanation for the internal structure of cometary nuclei.

EVIDENCE SUPPORTING THE FLUFFY AGGREGATE AND RUBBLE PILE MODELS

Evidence for both the "fluffy-aggregate" and "primordial-rubble-pile" models has continued to accumulate since the Halley spacecraft missions in 1986. Note that whether we use the term "fluffy aggregate" or "primordial rubble pile," we are referring to the same basic concept of a weakly bound aggregation of smaller icy cometesimals.

Comet Shoemaker-Levy 9

A particularly strong confirmation comes from the studies of comet Shoemaker-Levy 9 (SL-9) in 1993–94. This comet was discovered close to Jupiter and consisted of a string of ~21 independent nuclei moving together (Shoemaker et al. 1993; see Fig. 3). Orbital solutions showed that the comet was in an eccentric orbit about Jupiter, likely having been captured around 1929 (Chodas and Yeomans 1996). Moreover, extrapolating the orbit backward in time showed that in 1992 the comet had passed Jupiter at a distance of 1.31 Jupiter radii, well within the tidal Roche limit. Tidal disruption appeared to provide a ready explanation for the numerous small comets traveling together.

However, attempts to model the breakup of the parent nucleus encountered a variety of problems. It was not clear why the nucleus should have broken into so many pieces as it passed through the Roche zone. Models of hierarchal splitting (e.g., Sekanina 1994), could not account for the 21 independent fragments. Sekanina's model is particularly tenuous as it delayed the beginning of the disruption of the nucleus until two hours past perijove passage, well after the maximum tidal stress had begun to diminish and leaving little time for further hierarchal splitting.

Asphaug and Benz (1994) attempted to model the original nucleus as 21 discrete cometesimals, but found that this did not work as the cometesimals tended to reform into only a few nuclei following the tidal disruption as a result of gravitational clumping. But Asphaug and Benz (1994, 1996) and also Solem (1994, 1995) solved the problem by hypothesizing that the original cometary nucleus was composed of numerous, i.e., thousands, of smaller cometesimals that initially were either weakly bound or held together only by self-gravity.

Asphaug and Benz showed that as the progenitor rubble-pile nucleus approached Jupiter, it would be distorted into an ever-lengthening cigar-shape by the tidal forces from Jupiter's strong gravitational field. However, as the individual cometesimals of the nucleus moved away from the planet, the tidal forces would decrease and self-gravity between the cometesimals would again begin to dominate their interaction. The cometesimals would begin to aggregate back into larger bodies.

Most interestingly, Asphaug and Benz showed that the number of final "clumps" was a function of the bulk density of the original comet. For densities greater than ~1.5 g/cm^3, the cometesimals would all aggregate into a single nucleus. For densities < 0.3 g/cm^3, no aggregation would occur. The observed 21 fragments corresponded to a bulk density for the parent nucleus of 0.5–0.7 g/cm^3 if it was not rotating, or 1.0 g/cm^3 if the nucleus was rotating in a direct sense with a period of ~9 h. Retrograde rotation was ruled out by the dynamical model.

Additionally, the Asphaug and Benz model predicted a progenitor nucleus diameter of 1.5 km, based on the length of the string of comets when SL-9 was discovered in March 2003. This was considerably smaller than diameter estimates of 10 km from a kinematic model (Sekanina 1994, 1996) or 7.7 km from HST imaging (Weaver et al. 1994). A diameter of 1.5 km is a fairly typical (even small) nucleus diameter as compared with measured values (Weissman and Lowry 2003; Meech et al. 2004; Lamy et al. 2004), whereas 8–10 km represents a fairly large nucleus, and hence likely a much rarer event. Estimates of impact energy following the impact of the major reassembled nuclei on Jupiter in July 1994 arrived at diameter values of several hundred meters (Crawford 1997), consistent with the Asphaug and Benz prediction of a relatively small progenitor nucleus of 1.5 km in diameter.

Crater Chains

The rubble pile model for SL-9 also explained an entirely independent phenomenon, the existence of crater chains on the

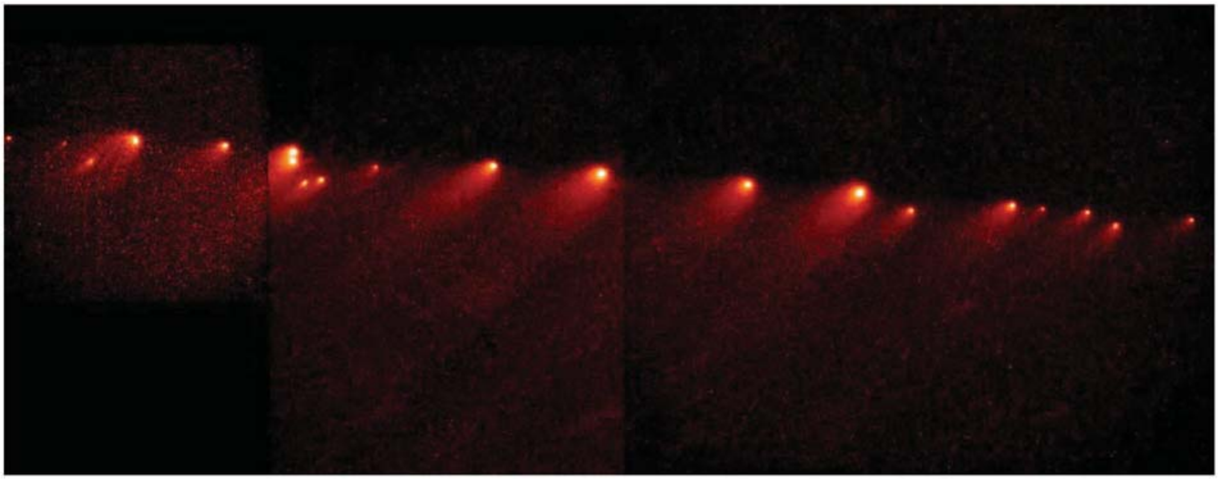

Fig. 3. Comet Shoemaker-Levy 9 as imaged by the Hubble Space Telescope in 1994 (Weaver et al. 1994). This comet was tidally disrupted when it passed 1.31 planetary radii from the center of Jupiter in 1992. Asphaug and Benz (1994, 1996) explained the breakup of the parent comet and the reassembly of the individual cometesimals into ~21 daughter nuclei using a rubble pile model of the nucleus consisting of thousands of small cometesimals.

surfaces of Ganymede and Callisto. These were first discovered by the Voyager spacecraft and later confirmed by the Galileo mission (Melosh and Schenk 1993; see Fig. 4). These chains are all on the Jupiter-facing hemispheres of the satellites. The chains are apparently formed by disrupted comets that reassemble after a passage through Jupiter's Roche zone, and then strike the satellites on their way out of the Jovian system. The string of reassembled comets forms a string of closely spaced or overlapping craters, much like a machine gun firing at a slowly moving target. Analyses by Schenk et al. (1996) showed that the median diameter of the progenitor comets of the observed crater chains was very close to the 1.5 km diameter estimated for SL-9. They also noted that the crater chains tend to have the largest impactors near the center of the chain, the same as observed for SL-9 and predicted by the Asphaug and Benz model.

The similarities between comet Shoemaker-Levy 9 and the crater chains demonstrate that they are different aspects of the same phenomenon: rubble-pile nuclei being tidally torn apart during passage through Jupiter's Roche zone, with subsequent reassembly into chains of comets moving together. The similarity in the estimated sizes of the parent nuclei suggest that this is a fairly common phenomenon involving typical cometary nuclei crossing Jupiter's orbit. Schenk et al. (1996) showed that the observed number of crater chains was consistent with the expected production rate from estimates of the flux of Jupiter-crossing comets.

Sungrazing Comets

Another case of tidally disrupted comets that sheds light on their internal structure are the sungrazing comets (Marsden 1989). These objects have perihelia within one solar radius of the solar surface: ≤ 0.01 AU. At this distance, they pass within the solar Roche limit. Prior to spaceborne observatories, only about a dozen of these sungrazers were known. Interestingly, eight of the known sungrazers found by ground-based observers had very similar orbits, suggesting that they could be fragments of a larger cometary nucleus that was tidally disrupted on a previous perihelion passage. These eight comets are collectively known as the Kreutz family. Some of the Kreutz family members were observed to split during their perihelion passages, e.g., comet Ikeya-Seki in 1965.

In 1982, analysis of coronagraphic images from the SOLWIND instrument on a U.S. Air Force research satellite revealed the existence of several more sungrazing comets, all of them in the same orbit as the Kreutz family (Michels et al. 1982). These objects did not survive perihelion passage; they had either been perturbed to orbits that impacted the Sun or had completely sublimated during their perihelion passage. Weissman (1984) showed that if sublimation was the removal mechanism, then the comets had to have radii less than ~15 meters.

Subsequently, the Solar Maximum Mission and the Solar Heliospheric Observatory (SOHO) have discovered more than 1,250 of these small sungrazers (mostly by SOHO; Biesecker et al. 2002, see Figure 5). Most are members of the Kreutz group. However, two additional groups have been recognized, known as the Kracht and Marsden groups. The parent comets of these three groups are not known. As with the SOLWIND comets, most objects do not survive perihelion passage, suggesting that they are likely small.

The behavior of the sungrazing comets is consistent with a rubble-pile structure for cometary nuclei. We can hypothesize that each of the parent comets was perturbed into a sungrazing orbit by a combination of stellar and galactic perturbations (all of the sungrazers are long-period comets). During perihelion

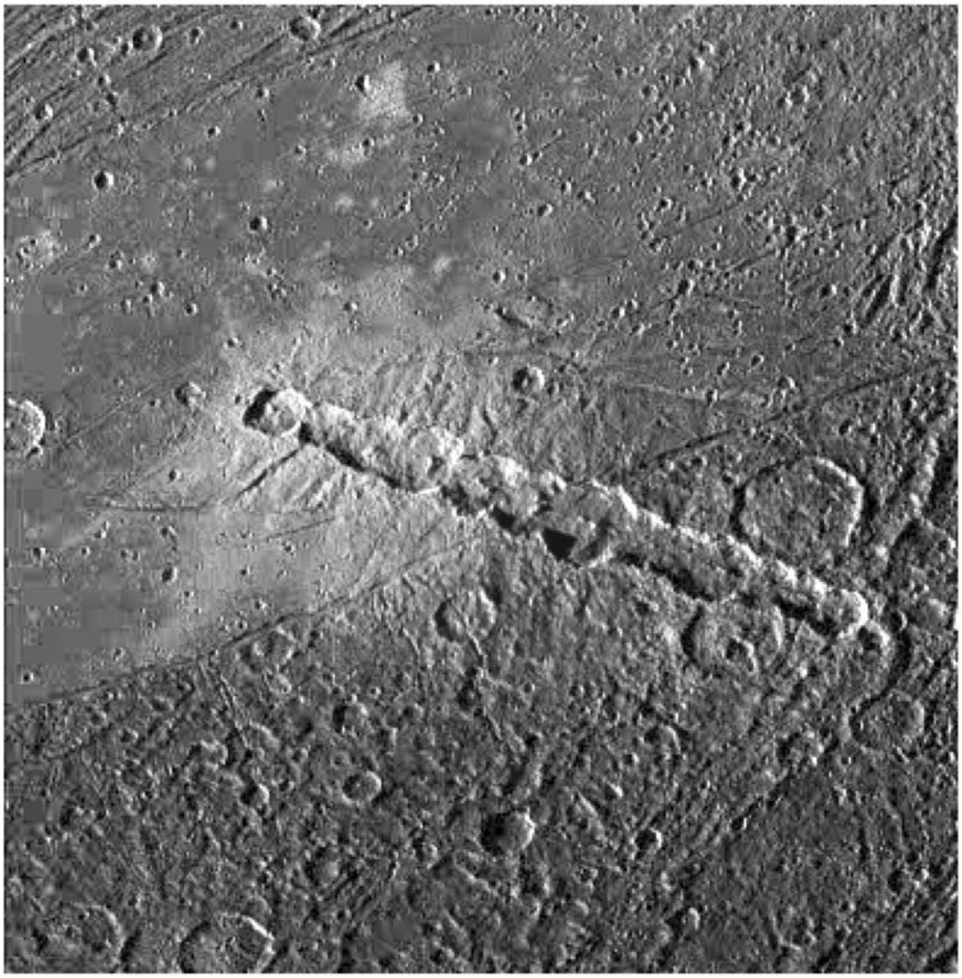

Fig. 4. Enki crater chain on the Jupiter-facing hemisphere of Ganymede as imaged by the Galileo spacecraft on April 5, 1997. The chain contains 13 distinct craters and is ~160 km long. These chains demonstrate that disruption and reassembly of cometary nuclei, as happened for Shoemaker-Levy 9 in 1992, is a general phenomenon that has occurred repeatedly at Jupiter.

passage, the parent comets were tidally disrupted and likely reformed into multiple independent nuclei, similar to what happened to comet Shoemaker-Levy 9. However, as in the case of SL-9, many cometesimals likely failed to be swept up by the reassembled nuclei. These, as well as the larger nuclei, have now spread out along the orbit of each parent comet, much like the particles in a meteoroid stream. This process may have repeated more than once as the daughter nuclei again returned to perihelion near the Sun. Weissman (1979) showed that the then known Kreutz family members needed to have made ~5 perihelion passages for nongravitational forces from outgassing to have reduced their semi-major axes to their current relatively small values of ~100 AU.

Random Disruption

Comets are also observed to disrupt at random times, when they are not deep within the gravity field of a planet or the Sun. Weissman (1980) examined observational records and showed that dynamically new comets from the Oort cloud split ~10% of the time, whereas returning long-period comets split ~4% of the time, and short-period comets split only 1% of the time. Weissman also showed that there was no correlation with time of perihelion passage or perihelion distance. In most cases, the parent comet survived after shedding some cometesimals, but in some cases the parent comet disappeared completely.

Perhaps the best known case of the latter was periodic comet 3D/Biela, which was seen on perihelion passages in 1772, 1805, 1826, and 1832. The comet was observed to split into two comets in 1846, returned as a double comet in 1852, and was never seen again, despite a well-determined orbit.

More recently, comet D/1999 S4 LINEAR was observed to disrupt spontaneously as it passed through perihelion in July 2000 at ~0.7 AU from the Sun (Fig. 6, Weaver et al. 2001). The comet's central coma region brightened and then began to stretch into a cigar-shaped cloud as Keplerian sheer spread the cometesimals making up the cometary nucleus along its orbital path. Weaver et al. (2001) estimated radii for the cometesimals of 25 to 60 m.

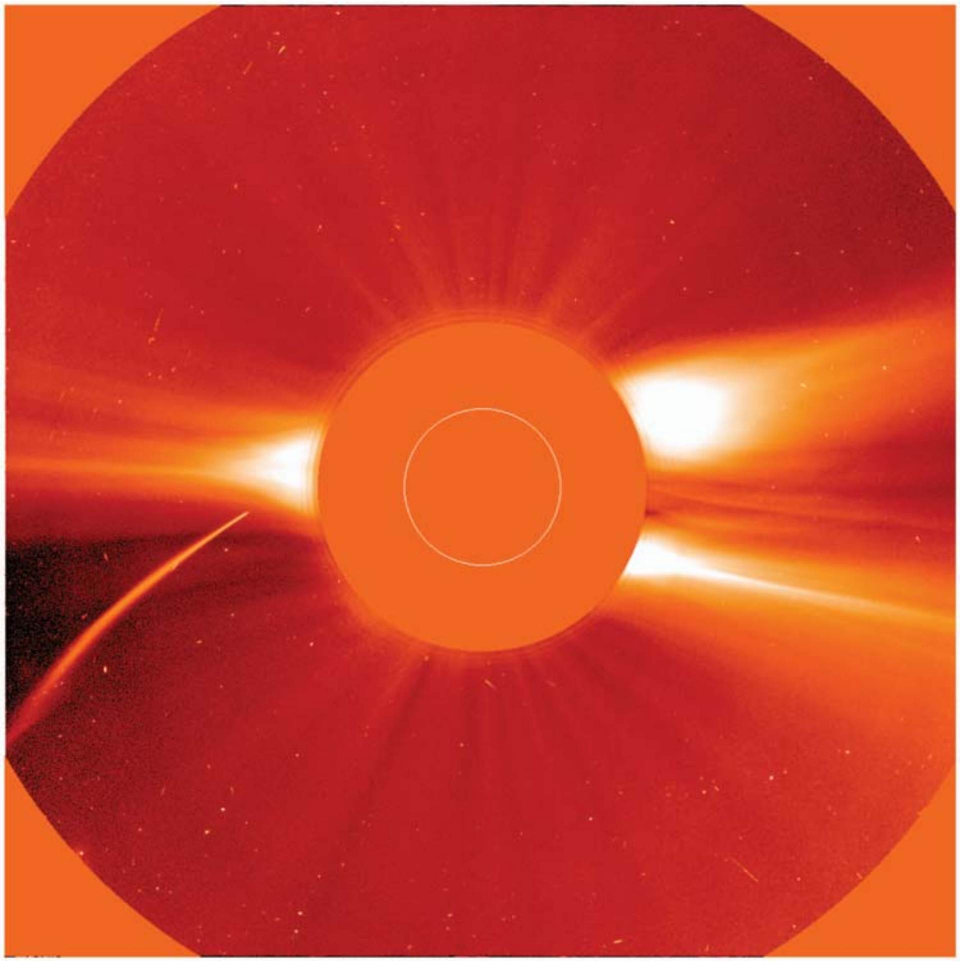

Fig. 5. Coronagraphic image of the Sun taken by the LASCO instrument onboard the Solar Heliospheric Observatory (SOHO) spacecraft on December 23, 1996, showing the solar corona and sungrazing comet C/1996 Y1. The position of the Sun is blocked by an occulting disk: the expected position of the Sun is shown by the circle centered on the disk. The projected field-of-view of the coronagraph is 8.4 million km in diameter. Over 1,250 of these small comets have been found by SOHO and other spacecraft. These ~10 meter diameter objects usually do not survive passage near the Sun. They are believed to be fragments of larger comets that were tidally disrupted during earlier perihelion passages. The ~10 m objects are similar in size to the smallest fragments found in the debris train flowing from comet Schwassmann-Wachmann 3-C by Weaver et al. (2006, Fig. 7).

Another very interesting recent example of splitting is comet 73P/Schwassmann-Wachmann 3. This Jupiter-family comet was discovered in 1930 and was observed to shed some pieces. In 1995 it underwent several large outbursts during perihelion passage and subsequently was seen to split into four major fragments. The 2001 apparition was poorly observed, but the comet passed very close to Earth in 2006 and four major fragments were recovered (although possibly not the same four as seen in 1995). Examination of the comet with the Hubble Space Telescope (Fig. 7) showed dozens of additional fragments, many of them relatively short-lived, suggesting that they were small, on the order of tens of meters in diameter.

It is clear that the superior spatial resolution of HST is now providing us with a far better view of cometary splitting events. We are now able to see small cometesimals shed from nuclei, which could not have been resolved with ground-based telescopes. In all likelihood, this has been happening all along but we could not observe these small fragments with the limited resolution of ground-based instruments. The observed statistics of the fraction of comets that split will likely be increased by this improved observational capability.

The cause(s) of random disruption are not known. Weissman et al. (2003) used a dynamical simulation to show that rotational spin-up due to torques from outgassing would cause a strengthless rubble pile nucleus to slowly shed cometesimals. After each shedding event the nucleus rotation would slow down because of the loss of angular momentum, but then speed up again due to the outgassing torques and the shedding event would repeat. Also, if the cometesimals were bonded together by some physical process (e.g., annealing, sintering), then the simulations showed that the entire nucleus would fly apart when the strength of those bonds was exceeded by the centrifugal forces.

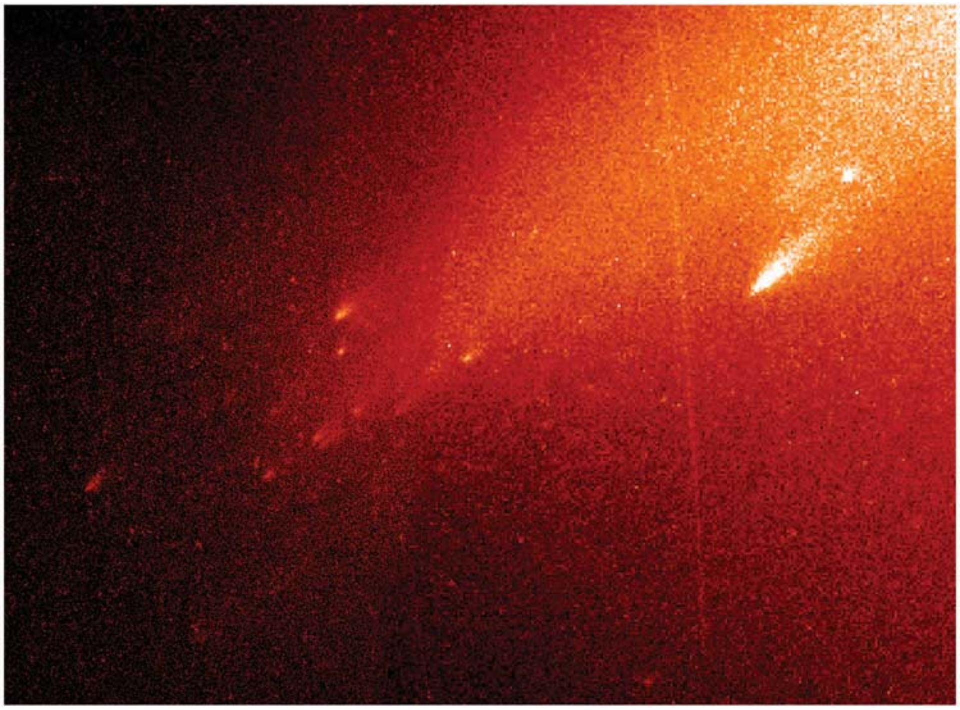

Fig. 6. Disrupted comet D/1999 S4 LINEAR disintegrated as it passed through perihelion in 2000 (Weaver et al. 2001). This HST image shows the tip of the nucleus cloud and the individual cometesimals that had previously made up the nucleus. Random disruption of cometary nuclei strongly suggests that the nuclei are indeed rubble piles.

Fig. 7. Hubble Space Telescope images of the disintegration of fragment B of the nucleus of comet 73P/Schwassmann-Wachmann 3 in 2006 (Weaver et al. 2006). This Jupiter-family comet was observed to break into several independent nuclei at its perihelion passage in 1995. The comet was not easily observable in 2001 but passed close to Earth in 2006, affording an excellent opportunity to observe the continued disintegration of the daughter nuclei. The estimated size of the individual fragments is ≥ 10 meters.

Another suggested mechanism for random disruption involves outbursts from pockets of highly volatile molecules trapped in the nucleus. While this may be feasible, it is not clear how one could develop large pockets of trapped volatiles if the nuclei were random aggregates of cometesimals with low bulk density and high porosity (see the Density of Cometary Nuclei section).

It is expected that the water ice in cometary nuclei forms in the amorphous state due to the relatively cold mean temperatures, < 100 K, in the cometary formation zones. As the nuclei approach the Sun and are warmed, this amorphous ice will exothermically convert to crystalline water ice at temperatures between ~120 and 160 K (Prialnik 1993; Prialnik et al. 2004). Thus, this provides a mechanism for outbursts in comets, particularly on their first few passages at small perihelion distances, < 5 AU. It may also account for the anomalous brightness of dynamically new long-period comets from the Oort cloud on the inbound legs of their orbits. However, the conversion is not self-sustaining, as the energy from the amorphous-crystalline ice conversion must also heat the colder ices at deeper depths below the nucleus surface, as well as the non-volatile dust and organics that are intimately mixed with the ice. Thus, it is unlikely that there is sufficient energy from this process to account for major disruption events affecting the entire nucleus.

Weissman's (1980) finding of a decrease in disruption rate with increasing dynamical age suggests that there may be some intrinsic property in some nuclei that makes them more susceptible to disruption on their first perihelion passage or soon thereafter, whereas a substantial number of nuclei appear to be immune to this weakness. Or, it may be that the nucleus components are somehow annealed during their first few perihelion passages, strengthening them against random disruption on later returns. These early disruption events (relative to dynamical age) may be linked to the presence of hyper-volatiles in the nuclei that are rapidly lost after the first and subsequent perihelion passages.

Regardless of the physical explanation for random disruption events, it is clear that they allow us to see in what manner a comet can disassemble itself. Nuclei are seen to break up into smaller nuclei and into very small pieces, on the order of 10 to several tens of meters in size. The daughter nuclei may then suffer additional disruption events and shedding on subsequent perihelion passages. The ease with which this appears to happen suggests a low bonding strength for the individual cometesimals.

DENSITY OF COMETARY NUCLEI

Density is a fundamental physical quantity that can tell us much about the internal structure and composition of a particular body. To determine the density, one of course needs to know the volume and the mass of the body. Volume estimates can be obtained from spacecraft imaging during flybys of cometary nuclei, though the derived shape model is often incomplete since 100% of the nucleus surface is not visible during the fast flyby. However, direct measurements of mass during the four fast flyby missions to date have not been possible because the gravity of the individual nuclei has been too weak to induce a measurable deflection of the trajectory of the spacecraft as they flew past the comets at high speed.

Thus, measurements of nucleus mass to date have relied on indirect methods. These include estimates derived from measurements and modeling of the nongravitational accelerations on the nuclei due to outgassing (Rickman 1986; Skorov and Rickman 1999), from modeling of the breakup and reassembly of comet Shoemaker-Levy 9 in 1992–94 (Asphaug and Benz 1994, 1996), and from examining the ensemble distribution of cometary rotation rates (Lowry and Weissman 2003; Snodgrass 2006). Most recently, the Deep Impact mission (A'Hearn et al. 2005) provided the closest approximation to a direct measurement when it measured the expansion rate of the ejecta plume from the DI impact event. We review the more prominent methods below. For a more complete review, please see Weissman et al. (2004).

Nongravitational Force Modeling

Density estimates based on nongravitational forces are obtained by first determining the nongravitational force parameters based on fitting orbital parameters for several successive perihelion passages of a particular nucleus. A model of the expected nongravitational forces is then developed based on the observed outgassing rate of that comet. The two are then combined to estimate the mass of the nucleus. If estimates of the nucleus dimensions are also known, they can be used to estimate the bulk density of the nucleus.

This was first done by Rickman (1986) for comet 1P/Halley and resulted in an estimate of only 0.1–0.2 g/cm^3. However, subsequent estimates for Halley by Sagdeev et al. (1988) and Peale (1989) found values of 0.6 (+0.9, −0.4) g/cm^3 and 0.03–4.9 g/cm^3, with a preferred value near 1.0 g/cm^3, respectively. Additionally, a later, more refined model by Skorov and Rickman (1999) found values of 0.5–1.2 g/cm^3 for comet Halley.

More recently, Farnham and Cochran (2002) found a value of 0.49 (+0.34, −0.20) for comet 19P/Borrelly based on a combination of ground-based and spacecraft observations. Alternatively, Davidsson and Guiterrez (2003) estimated a bulk density of 0.18–0.30 g/cm^3 for Borrelly, barely in agreement with Farnham and Cochran at the one-sigma level. Davidsson et al. (2007) also estimated a bulk density of 0.45 ± 0.25 g/cm^3 for comet 9P/Tempel 1, based on nongravitational force modeling.

The nongravitational force models do demonstrate that comets likely have low densities, but the estimated values have large error bars and poor consensus on the actual values. This likely results because of the large number of free parameters in the models of the nongravitational forces (e.g., thermal inertia, surface roughness, momentum coupling, etc.), plus the uncertainty in measured gas production rates throughout the orbit, the dust-to-gas ratio, and other poorly determined observational constraints.

Comet Shoemaker-Levy 9

As described above, the breakup of comet Shoemaker-Levy 9 in 1992 (see the Evidence Supporting the Fluffy Aggregate and Rubble Pile Models section) provided a valuable opportunity to study both the internal structure and bulk density of a cometary nucleus. As discussed previously, Asphaug and Benz (1994, 1996) and Solem (1994, 1995) each developed rubble pile models of the original nucleus and found bulk density values of 0.5–0.7 g/cm^3, or a somewhat higher value of 1.0 g/cm^3 if the nucleus was rotating in the direct sense with a period of ~9 hours. These models were able to explain many observed features of the SL-9 comet chain, including the fact that the largest daughter nuclei were near the center of the chain. Additionally, the models provided an explanation for observed crater chains on the surfaces of Ganymede and Callisto (Melosh and Schenk 1993; Schenk et al. 1996).

Rotational Limits

If one assumes that cometary nuclei are strengthless (or very weakly bonded) rubble piles, then lower limits on the bulk density of cometary nuclei can be obtained by measuring their rotation rates and axial ratios. Note, that here we are referring to the binding strength between individual cometesimals, and not the material strengths of the cometesimals themselves; the latter is likely much higher than the former. A nucleus spinning too fast will fly apart due to centrifugal forces. Weissman et al. (2003) performed computer simulations of rotational spin-up of rubble-pile nuclei and suggested this as a mechanism to explain cometary splitting.

Pravec et al. (2002) showed that a rotational breakup limit exists for most small asteroids at a period of ~2.2 hours. The only exceptions are very small asteroids less than 150 meters in diameter (and one asteroid at ~900 meter diameter) that are believed to be coherent, monolithic objects (Note that the largest size for these monolithic asteroids is within a factor of a few of the tens of meters size estimated for the cometesimals that make up cometary nuclei). The 2.2 hour rotation rate limit corresponds to a bulk density of ~2.5 g/cm^3. This density value is somewhat less than that measured for ordinary chondrite meteorites, which have average bulk densities of 3.19–3.40 g/cm^3 (Britt et al. 2002), suggesting an underlying rubble pile structure for the asteroids. A more complete discussion of asteroid densities is presented in Britt et al. (2002), who also report on estimated densities and porosities of larger asteroids and asteroids with satellites, in those cases where their masses have been directly measured.

Compilations of the measured rotation rates and shapes of cometary nuclei have most recently been presented by Lowry and Weissman (2003) and Snodgrass (2006). A plot of rotation period versus axial ratio for 20 cometary nuclei from Snodgrass (2006) is shown in Fig. 8. Nineteen of the 20 comets have rotation periods and shapes consistent with a bulk density < 0.6 g/cm^3. The one object with a higher lower-limit to its density is comet 133P/Elst-Pizarro. This is easily explained as this object is, in reality, an outer main belt, volatile-rich asteroid, where buried volatiles have likely been exposed by an impact. This is consistent with the fact that, at a semi-major axis of 3.16 AU, Elst-Pizarro is a member of the Themis collisional family, one of the largest families in the asteroid belt.

Interestingly, the Centaurs and Kuiper belt objects with measured rotation periods and shapes exhibit a similar distribution with an apparent cut-off at a density of 0.6 g/cm^3 (Snodgrass 2006). This is expected since the Centaurs are thought to be Scattered disk and Kuiper belt objects evolving to JFC-type orbits. The one exception, (136108) 2003 EL61, is a very large Kuiper belt object approximately 1,500 km in diameter, where self-gravity has almost certainly provided internal compression.

Note in Fig. 8 that there is a lack of cometary nuclei with large axial ratios close to the rotation limit corresponding to a density of 0.6 g/cm^3. This mimics the behavior observed for small asteroids (Pravec and Harris 2000) and is again attributed to an underlying rubble pile structure.

The Deep Impact Experiment

The most recent estimate of the density of a cometary nucleus comes from the Deep Impact mission, which encountered comet Tempel 1 on July 4, 2005 and delivered a 370 kg impactor to the nucleus surface at a velocity of 10.3 km/sec (A'Hearn et al. 2005). The resulting impact was estimated to have an energy of ~19 Gigajoules, equivalent to ~4.8 tons of TNT, and produced a rapidly expanding cloud of dust and gas at the impact site. Following the flyby, the DI spacecraft turned to look back at the nucleus and observed the expanding ejecta plume at T = impact + 45 min, and impact + 75 min.

The DI investigators estimated the gravity, and hence the mass of the Tempel 1 nucleus based on the observed expansion rate of the ejecta plume in the look back images, under the assumptions that the base of the ejecta plume was still attached to the nucleus (the view of the base of the plume was occulted by the nucleus limb in the look back images) and that the impact was a gravity-dominated rather than a strength-dominated event (Richardson et al. 2007). The resulting estimate was 0.20–1.0 g/cm^3, with a preferred value of 0.40 g/cm^3. The preferred value is somewhat less than some of the estimates given above but the error bars are easily consistent with the value of 0.6 g/cm^3.

The available evidence strongly suggests that cometary nuclei have bulk densities less than 1.0 g/cm^3, with a most likely value of 0.6 ± 0.2 g/cm^3. This is considerably less than the value of 1.65 g/cm^3 for fully packed cometary material as estimated by Greenberg (1998), and implies combined micro- and macro-porosities of ~50–75%. These values are somewhat to substantially greater than the upper limit of ~40% observed for carbonaceous chondrite asteroids (Britt et al. 2002), the closest compositional analog to cometary nuclei. However, the far larger sizes of the C-type asteroids with measured masses, the different thermal and compositional regimes in which asteroids formed as compared with cometary nuclei, as well as the presence of substantial ices in comets, may account for these differences.

RESULTS FROM SPACECRAFT ENCOUNTERS

All of the encountered nuclei to date are short-period comets, those with orbital periods < 200 yr, and with well-determined orbital parameters, a pre-requisite for a spacecraft

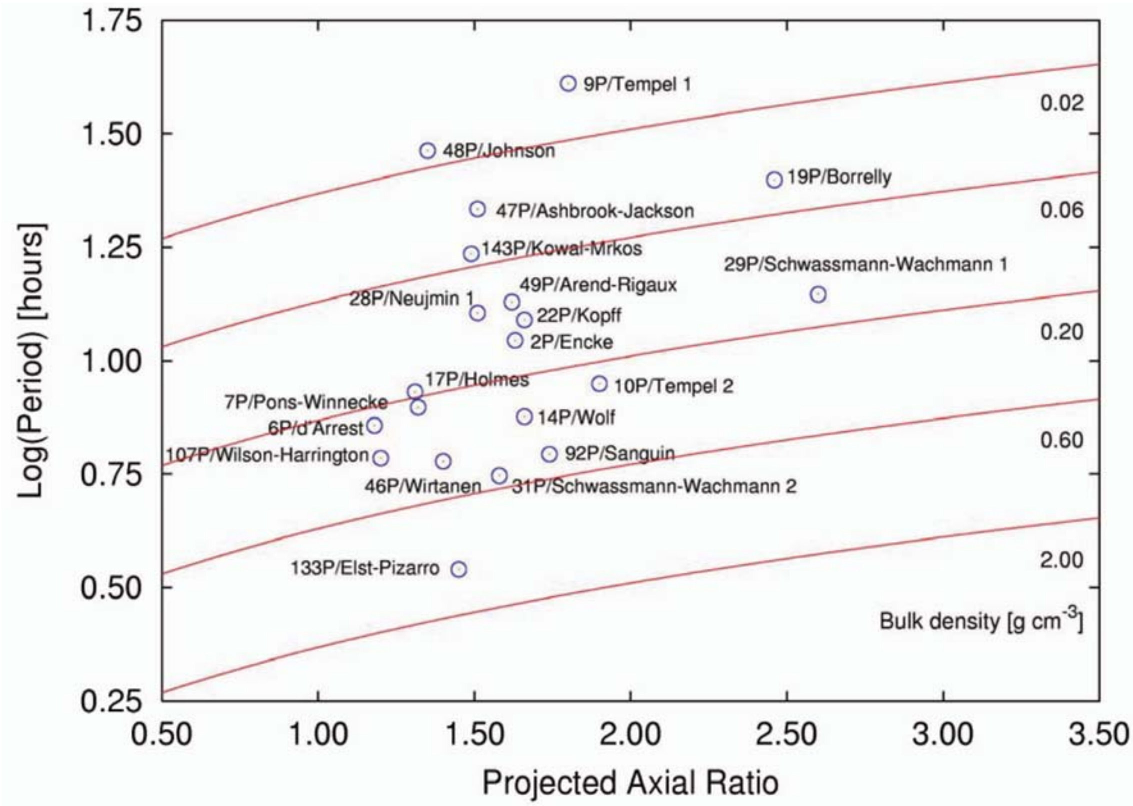

Fig. 8. Measured rotation periods of cometary nuclei versus their projected axial ratios, a/b, as compiled by Snodgrass (2006). The plotted contours indicate the bulk density of a strengthless rubble pile nucleus that can survive disruption by centrifugal forces. All but one nucleus has an implied lower limit on its density of less than 0.6 g/cm^3. The one exception is comet 133P/Elst-Pizarro, which is actually a volatile-rich asteroid in the outer main belt, actively outgassing because buried volatiles have been exposed, probably by an impact event. This object likely contains a lower fraction of ices than do typical comets (formed much farther out in the solar system) and thus is expected to have a higher bulk density.

mission. More specifically, 1P/Halley is the archetype of the "Halley-type comets" (HTCs) with orbital periods between 20 and 200 years, and a wide range of orbital inclinations, though not quite fully randomized, as are the orbits of the long-period comets (periods > 200 yr). The other three encountered nuclei are all Jupiter-family comets (JFCs) with orbital periods < 20 yr and fairly low to moderate inclinations (Levison 1996).

The origin of the JFCs has been shown by dynamical simulations to most likely be the Scattered disk and the Kuiper belt, two collections of remnant icy planetesimals near and beyond the orbit of Neptune that did not have time to form into a planet. This resulted because Neptune's gravity raised the relative encounter velocities of these planetesimals from the low values necessary for collisional accretion to the higher values that resulted in collisional erosion and disruption. More specifically, the JFCs are believed to derive primarily from the Scattered disk population, which have perihelia close to the orbit of Neptune and are actively interacting with that planet dynamically. The source of the Scattered disk population is believed to be the Kuiper belt interior to about 35 AU, and the Uranus-Neptune zone planetesimals, most of which were ejected during the clearing of the giant planets zone in the first billion years of the solar system's history.

The source of the Halley-type comets is less certain and may be a mix of Kuiper belt, Scattered disk, and Oort cloud comets. The Oort cloud is a vast spherical cloud of comets surrounding the solar system and extending to interstellar distances (Oort 1950). The source of the Oort cloud is believed to be icy planetesimals ejected from the giant planets zone during the first billion years of the solar system's history (Kuiper 1951; Dones et al. 2004). Orbits in the Oort cloud are so far from the Sun that they are perturbed by random passing stars and the galactic tide. Over the history of the solar system, these perturbations have totally randomized the orbits of the comets in both inclination and eccentricity. The Oort cloud is the source of the long-period comets.

All of the spacecraft encounters with cometary nuclei to date have been flyby missions, brief snapshot views of the nuclei and surrounding comae. Although the scientific contributions of each mission have been substantial, the high flyby speeds and the relatively small size of the nuclei precluded a determination of the masses of the nuclei. Thus, no direct density estimates, which would have provided clues to the internal structure of the nuclei, were possible. However, in the case of 9P/Tempel 1, the mass was estimated from the expansion rate of the ejecta plume created by the impact experiment and the volume from spacecraft imaging, resulting in the density estimate discussed above (see the Density of Cometary Nuclei section).

Imaging of the gross shape of the nuclei reveals a diverse collection of irregularly shaped bodies. In the case of 1P/Halley and 19P/Borrelly, the nuclei appear to have a binary structure, i.e., they are aggregations of two (or more) smaller icy planetesimals. The nucleus of 81P/Wild 2 appears to be more ellipsoidal, while the nucleus of 9P/Tempel 1 is irregularly shaped but appears to be a single body.

However, appearances can be deceiving. Consider the lessons learned from flyby studies of the physical properties of asteroids. To date, six asteroids have been encountered by planetary spacecraft: 951 Gaspra and 243 Ida by Galileo, 265 Mathilde and 433 Eros by NEAR, 5535 Annefrank by Stardust, and 25143 Itokawa by Hayabusa. All of these asteroids appear to be single, compact bodies, with the exception of 25143 Itokawa, which does appear to be a rubble pile (Note that this conclusion is tenuous for 5535 Annefrank because of the low resolution of the images.) However, in four of these cases it has been possible to measure the mass of the asteroids, and in all of those cases, the asteroids have been shown to be underdense as compared with meteorite samples from the same taxonomic class, with suggested porosities of 20–30% (Britt et al. 2002). It appears that regolith can be very effective at hiding the fractured and/or rubble pile internal structure of these bodies.

The problem of understanding the spacecraft imagery is complicated by the different spatial resolutions achieved at each body, ranging from a best value of ~80m/pixel for parts of 1P/Halley down to only a few meters per pixel for parts of 9P/Tempel 1. Comet 1P/Halley's nucleus most clearly appears to be a rubble pile structure, with large topographic features and, at least, a binary shape. About 30% of the illuminated surface is active, with large, apparently collimated jets (Keller et al. 1986; Sagdeev et al. 1986). The remainder of the surface appears inactive and is likely covered by a lag deposit crust of large particles that serve to insulate the icy-conglomerate material at depth.

The nucleus of 19P/Borrelly also has a binary shape but has a smoother surface with less topography and some evidence of erosional processes (Soderblom et al. 2002; Britt et al. 2004). In addition to chaotic terrain, Borrelly displays mesa-like structures on its surface with smooth, flat tops and steep walls. It has been suggested that the walls of the mesas are where sublimation is currently taking place. In contrast to Halley, only a few percent of the nucleus surface appears to be active.

Comet 81P/Wild 2 has a fairly ellipsoidal shape but a very unusual surface morphology, covered by numerous shallow and deep depressions, most with flat floors, that may be either eroded impact craters or sublimation pits, or some combination of the two (Brownlee et al. 2004). Large blocks protruding from the surface also suggest an underlying rubble pile structure. The orbital history of 81P/Wild 2 suggests that it may be a relatively young JFC, having been thrown into the terrestrial planets region after a close encounter with Jupiter in 1971, and thus the surface may preserve features that are truly primitive. The coma images of Wild 2 also show numerous jets but they have not yet been identified clearly with surface features.

The highest resolution images to date are of the nucleus of comet 9P/Tempel 1. These images reveal a complex surface morphology with strong evidence for geological processes including erosion and mass movement (A'Hearn et al. 2005). There also appears to be two relatively well-defined and large (~300 m in diameter) impact craters on the surface, somewhat surprising since it was assumed that impacts were rare on such a small body, and that sublimation would quickly erode such features. Apparent layering in the surface images may be primitive, but more likely is further evidence of erosional processes acting on the nucleus. Also, there are features that suggest material flowing across the nucleus surface, in particular flowing "downhill" (Veverka et al. 2006). Some surface features on Tempel 1 resemble those on Borrelly and this may be consistent with both nuclei being older and more evolved, having had a long residence time in the terrestrial planets zone.

DISCUSSION AND SUMMARY

In this paper we have presented evidence that strongly supports two proposed models for the interior structure of cometary nuclei: the fluffy-aggregate model of Donn et al. (1985) and the primordial rubble pile model of Weissman (1986). In essence, these are really one and the same model, arrived at from different starting points but both describing cometary nuclei as weakly bonded aggregates of large numbers of smaller icy-conglomerate cometesimals.

This description is able to explain a number of observed phenomena in comets: 1) the disruption and reassembly of the nuclei of comet Shoemaker-Levy 9; 2) the crater chains on the Galilean satellites that result from SL9-like comets impacting on the satellites as the tidally disrupted and reassembled comets move away from Jupiter; 3) the existence of cometary families of sungrazing comets, consisting of larger nuclei as well as hundreds of individual cometesimals spread along the same orbit like a meteoroid stream; 4) random disruption of cometary nuclei where comets are observed to shed many smaller, short-lived nucleus fragments; 5) the low density estimates for cometary nuclei obtained through a variety of methods; 6) the lack of observed nuclei spinning with periods less than ~5.2 hours, analogous to the ensemble behavior of small asteroids (where the spin limit is ~2.2 hours); and 7) spacecraft imaging of cometary nuclei that show evidence for binary structure (in two of four cases), as well as chaotic and often highly irregular surface morphology.

Additionally, theoretical modeling and estimates of the accretion process (Donn et al. 2005) predicts a porous, aggregate-like structure. There is a lack of energy sources in the early solar system available to modify this primitive structure of small planetesimals into a single, coherent body (Weissman 1986). Lastly, studies of the collisional histories of objects in the Kuiper belt and in the giant planets zone during the ejection of icy planetesimals to the Oort cloud (Stern 1995, 1996; Farinella and Davis 1996; Stern and Weissman, 2001; Charnoz and Morbidelli 2007) show that both populations experienced an intense collisional environment, similar to the one that has produced the rubble pile asteroids.

Continued ground-based and orbiting telescope studies of comets are likely to add to the evidence we have supporting a rubble pile model for cometary nuclei. However, the final resolution of this question likely requires the detailed study of a cometary nucleus (preferably many nuclei) at close range, something that can only be accomplished using a nucleus orbiting spacecraft, and perhaps may even require a nucleus lander.

The Rosetta mission of the European Space Agency (Glassmeir et al. 2007) includes experiments designed to investigate the internal structure of the nucleus of periodic comet 67P/Churyumov-Gerasimenko (hereafter, 67P/CG). Rosetta, launched on March 2, 2004, is slowly making its way to a rendezvous with 67P/CG in August 2014. A key experiment is the Comet Nucleus Sounding Experiment by Radiowave Transmission (CONSERT; Kofman et al. 2007). CONSERT is a radar tomography experiment consisting of a transponder on the Rosetta lander and a radar transmitter/receiver on the Rosetta orbiter. If the lander is able to survive several weeks or months on the nucleus surface, it will allow the orbiter sufficient time to orbit the rotating nucleus many times, obtaining numerous ray paths through the nucleus. The experiment is somewhat hampered by the fact that there is only one nucleus lander (two were originally planned). However, CONSERT should yield considerable insight into the interior of the 67P/CG nucleus, including the location and dimensions of any substantial voids.

The gravity mapping experiment onboard Rosetta will provide additional evidence on the internal structure of the nucleus (Pätzold et al. 2007). Mapping of higher harmonics in the 67P/CG gravity field, coupled with a detailed shape model obtained from the Rosetta imaging experiment, OSIRIS (Keller et al. 2007), will provide evidence of density inhomogeneities within the nucleus, as well as an overall measure of the bulk density of the nucleus. The Rosetta spacecraft may orbit as close as 1 km to the surface of 67P/CG.

A third source of information is OSIRIS, the imaging experiment onboard Rosetta (Keller et al. 2007), which will provide sub-meter resolution images of the nucleus surface. These images should provide sufficient resolution to understand the mechanisms creating the nucleus surface morphology, and may provide evidence of faults, substructure, or other landforms that help to reveal the internal structure of the nucleus.

Lastly, the experiments onboard the Rosetta lander (Bibring et al. 2007) will provide critical information on the physical properties of the nucleus materials, including composition and strength, especially when coring and sampling beneath the surface down to ~70 cm. Rosetta will provide a quantum leap forward in our understanding of comets and in particular on the questions of the internal structure and density of a typical cometary nucleus.

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