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The internal structure of Jupiter family cometary nuclei from Deep Impact observations: The "talps" or "layered pile" model

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Abstract

We consider the hypothesis that the layering observed on the surface of Comet 9P/Tempel 1 from the Deep Impact spacecraft and identified on other comet nuclei imaged by spacecraft (i.e., 19P/Borrelly and 81P/Wild 2) *is ubiquitous on Jupiter family cometary nuclei and is an essential element of their internal structure*. The observational characteristics of the layers on 9P/Tempel 1 are detailed and considered in the context of current theories of the accumulation and dynamical evolution of cometary nuclei. The works of Donn [Donn, B.D., 1990. Astron. Astrophys. 235, 441–446], Sirono and Greenberg [Sirono, S.-I., Greenberg, J.M., 2000. Icarus 145, 230–238] and the experiments of Wurm et al. [Wurm, G., Paraskov, G., Krauss, O., 2005. Icarus 178, 253–263] on the collision physics of porous aggregate bodies are used as basis for a conceptual model of the formation of layers. Our hypothesis is found to have implications for the place of origin of the JFCs and their subsequent dynamical history. Models of fragmentation and rubble pile building in the Kuiper belt in a period of collisional activity (e.g., [Kenyon, S.J., Luu, J.X., 1998. Astron. J. 115, 2136–2160; 1999a. Astron. J. 118, 1101–1119; 1999b. Astrophys. J. 526, 465–470; Farinella, P., Davis, D.R., Stern, S.A., 2000. In: Mannings, V., Boss, A.P., Russell, S.S. (Eds.), Protostars and Planets IV. Univ. of Arizona Press, Tucson, pp. 1255–1282; Durda, D.D., Stern, S.J., 2000. Icarus 145, 220–229]) following the formation of Neptune appear to be in conflict with the observed properties of the layers and irreconcilable with the hypothesis. Long-term residence in the scattered disk [Duncan, M.J., Levison, H.F., 1997. Science 276, 1670–1672; Duncan, M., Levison, H., Dones, L., 2004. In: Festou, M., Keller, H.U., Weaver, H.A. (Eds.), Comets II. Univ. of Arizona Press, Tucson, pp. 193–204] and/or a change in fragmentation outcome modeling may explain the long-term persistence of primordial layers. In any event, the existence of layers places constraints on the environment seen by the population of objects from which the Jupiter family comets originated. If correct, our hypothesis implies that the nuclei of Jupiter family comets are primordial remnants of the early agglomeration phase and that the physical structure of their interiors, except for the possible effects of compositional phase changes, is largely as it was when they were formed. We propose a new model for the interiors of Jupiter family cometary nuclei, called the *talps* or "layered pile" model, in which the interior consists of a core overlain by a pile of randomly stacked layers. We discuss how several cometary characteristics—layers, surface texture, indications of flow, compositional inhomogeneity, low bulk density low strength, propensity to split, etc., might be explained in terms of this model. Finally, we make some observational predictions and suggest goals for future space observations of these objects.

Keywords: Comets; Comets, nucleus; Comet Tempel-1; Comets, origin; Kuiper belt

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1. Introduction

The apparent diversity in the appearance of three Jupiter family and one Halley family comet nuclei that were recently visited and imaged by spacecraft (Fig. 1) has been widely commented on, e.g., Weaver (2004), Brownlee et al. (2004). But perhaps more significant, and certainly more difficult to discern, are the underlying *similarities* that exist between the three Jupiter family comets. As is discussed by Thomas et al. (2007) and elsewhere in this issue, among the dominant landforms on 9P/Tempel 1 are exposed layers that appear to be deep seated and surface layers bounded by what appear to be backwasting scarps. In Fig. 2 we mark the boundaries of distinct layers to illustrate their widespread occurrence.

On 19P/Borrelly, where the evidence, seen at lower spatial resolution, is less clear, Britt et al. (2004) report the presence of smooth plains and multiple, ∼100-m-high, mesa-like structures bounded by scarps. These scarps, they suggest, could be backwasting and be the main contributor to sublimational mass loss. On 81P/Wild 2 Brownlee et al. (2004) report the presence of large flat-floored features surrounded by steep cliffs ∼100 m high (which they interpret as possible impact craters), mesas in the Shoemaker basin, and evidence for "stratification" and "layering" in the region of the "right foot." They suggest that Wild 2 may be stratified at different scales. For our own part it seems possible, although clearly speculative, that the upper level topography seen in the Wild 2 landscape can also be interpreted as an interconnected mesa-like feature in a relatively early stage of development. Thus the steep sided walls that enclose "pits" and "craters" might also be interpreted as retreating scarp boundaries created by erosion from sublimation centers that have yet to interconnect on a global scale.

In the case of 1P/Halley, the masking of geological features by coma structures and the significantly lower spatial resolution make any geological analysis difficult. Keller et al. (1995) discuss a few resolved features that are 500–1000 m in extent and speculate (their word) that "... this is not fortuitous and that the typical size is a relic of the formation of the comet, indicating the mean size of the blocks that coalesced and formed the nucleus during the creation of the Solar System." This is a theme that we shall return to in our discussion of a "layered pile" model in Section 4. Weissman et al. (2004) identify "hills" and a "flat area" but the description of topography does not allow definitive geological inferences to be confidently made.

Taken together the similarities in these various observations provide us with sufficient basis to investigate the hypothesis *that the presence of layers, like those seen on 9P/Tempel 1, is ubiquitous on Jupiter family cometary nuclei and is an essential element of their internal structure*. We specifically do not extend this hypothesis to all cometary nuclei for two reasons. First, the evidence from 1P/Halley (a long period and possibly Oort cloud comet) is insufficient and secondly, a different accumulation and early post-accumulation environment may apply in the source region for Oort cloud comets than in the source region for JFCs (Jupiter family comets). A physical distinction between the interior structures of the two kinds of comets is quite conceivable.

The spacecraft images of 19P/Borrelly, 81P/Wild 2, and 9P/Tempel 1, particularly at higher spatial resolution, clearly question the current paradigm that has been proposed for the internal structure of cometary nuclei, i.e., that of a collisionally processed fractal aggregate or primordial rubble pile (Weissman et al., 2004). Both Weaver (2004), in a published perspective, immediately after the images of Wild 2 became available, and Brownlee et al. (2004) have raised this issue. Weissman et al.'s collisionally evolved primordial rubble pile model concept is an effort to achieve a consensus on a working model for cometary interiors that takes into account their presumed origin, their physical and dynamical histories, and how they behave near the Sun and under tidal stress, i.e., the phenomenon of "splitting." When they wrote, Weissman et al. had available to them the images of Comets Halley and Borrelly from which they derived direct evidence for their model concepts—these were the roughness of the surfaces of the two comets and indications of a bimodal structure (in a brief note added in proof they also show and refer to the Wild 2 images pointing out the presence of irregular blocks and possible sublimational features).

We now have had time to study and compare the pictures of Wild 2 and Tempel 1, which certainly show evidence of surface roughness but are, at least in the latter case, dominated by global scale layering. Can this layering be explained in terms of models that reflect an active collisional history such as that envisioned by Stern (1993, 1995) or, for example, by Farinella and Davis (1996) and Davis and Farinella (1997) and which is at the basis of the collisionally modified primordial rubble pile concept? Or, alternatively, can the gentle accumulation, partially compressive, interpenetration model of Donn and Hughes (1986) and Donn (1990, 1991) provide an explanation for the layers without further evolution? Possibly, but with difficulty. In both cases the description of the accumulation or subsequent collisional processes do not easily allow for the implied order in the growth of a sequence of superposed layers such as is observed.

In this paper the nature of the collisions of primordial aggregates with the growing nucleus takes a central role and it is in the details of this process that we seek to find the origin of the layers. In our concept fractal aggregates colliding with a growing nucleus only minimally interpenetrate but can have their macroscopic structure massively deformed into layers while retaining their microscopic granular character. To explain how these layers persist through their ∼4 byr storage time in the outer Solar System we suggest two possibilities: (i) a revision in the collisional fragmentation outcome model and/or (ii) long-term residence in the scattered disk where the collisional environment might be less severe (Rickman, 2004). The scattered disk, an extended distribution of trans-neptunian objects characterized by high eccentricities, has already been proposed by Duncan and Levison (1997) as the primary source of the observed JFCs.

We consider our hypothesis in the context of current ideas of the physical and dynamical evolution of cometary nuclei and

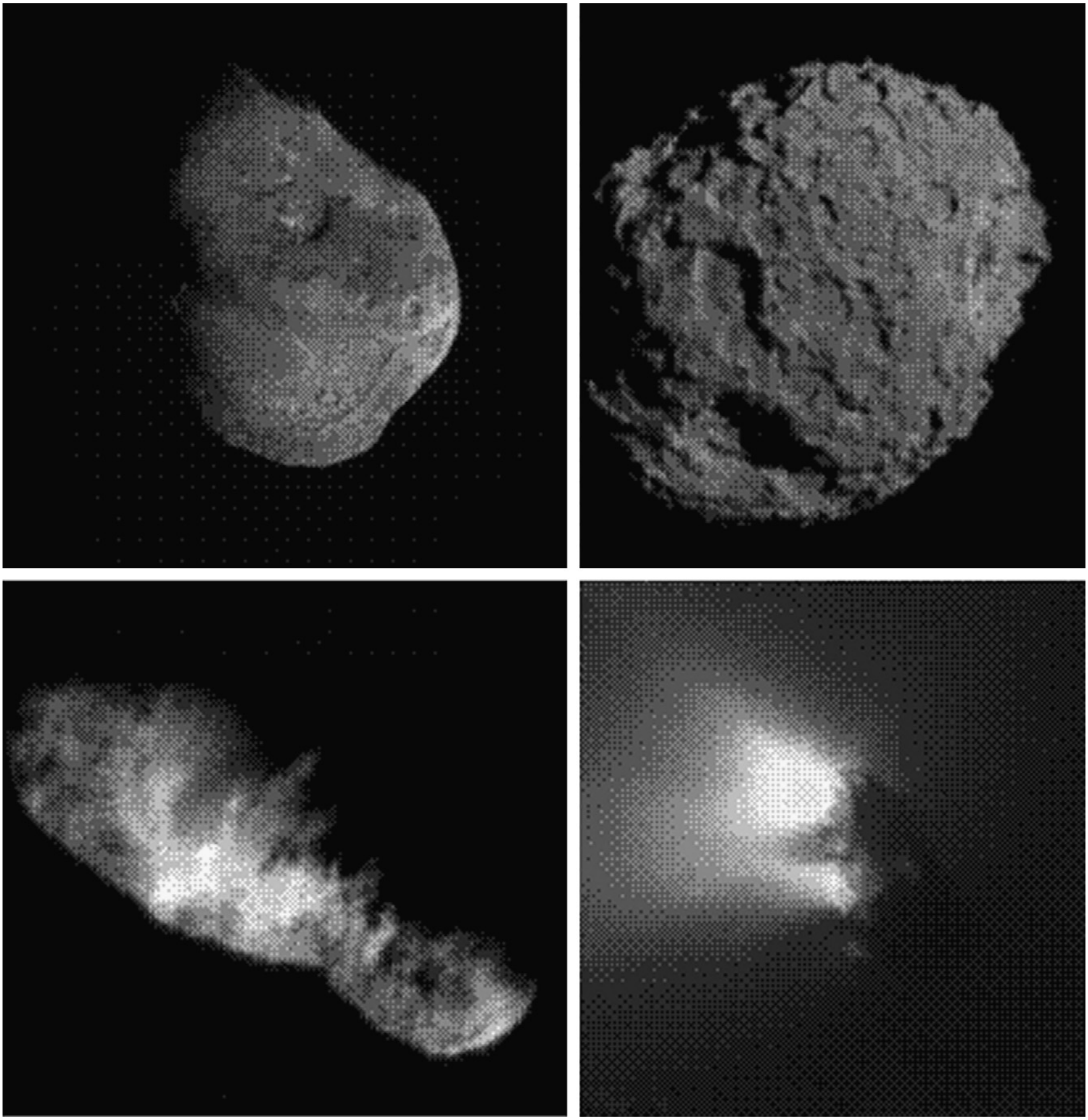

Fig. 1. Three Jupiter family cometary nuclei and Comet 1P/Halley. *Bottom right*: 1P/Halley. The spatial resolution varies across the image from 50 to 320 m/pixel (after Keller et al., 1995). The mean radius is 4.6 km. *Bottom left*: 19P/Borrelly at a resolution of ~47 m/pixel (after Soderblom et al., 2004). The mean radius is 2.2 km. *Top right*: 81P/Wild 2 at a resolution of ~20 m/pixel (after Brownlee et al., 2004). The mean radius is 2.0 km. *Top left*: 9P/Tempel 1 at a resolution of ~10 m/pixel (after A'Hearn et al., 2005). The mean radius is 3.0 km. The wide diversity in shape and landforms on these three objects appears obvious in these views although somewhat masked by the differences in image resolution. Less obvious are the similarities that exist (*see text*).

arrive at a substantial modification of the original Weissman (1986) primordial rubble pile model while continuing to embrace the ideas of fractal growth and interpenetration (Donn, 1990) during the early stages of accumulation. The hypothesis leads to a concept in which the later stages of accumulation are dominated by the creation of a random stack of superposed layers over a fractal core. In Section 2 we lay out the observed properties of the layers as well as they can be determined. In Section 3 we consider these properties in terms of current views of the physical and dynamical evolution of Jupiter family cometary nuclei, and in Section 4 we propose a new paradigm for the general structure of their interiors and introduce the word "talps" to distinguish primordial layers from any which may have formed on more recent geological timescales. Talps is a synonym (http://www.psuedodictionary.com) of the word "splat" an onomatopoeia that only approximates what we are proposing. We also briefly discuss in this section how the properties of this model might explain many of the commonly observed features of comets as they approach the Sun. Finally, in Section 5 we make suggestions and predictions for future investigations.

Fig. 2. *Left:* 9P/Tempel 1 as seen by the Deep Impact cameras with the boundaries of obvious layers marked. Small letters have been superposed on some of the layers so that they can be identified in the text. *Center:* Same figure but with the boundaries removed for clear viewing of the surface features. *Right:* 9P/Tempel 1 with the nucleus equatorial coordinate system superposed for easy reference in the text.

2. Observed and inferred properties of cometary layers

In Fig. 2 (left) we identify scarps that, under our hypothesis, represent the current boundaries of layers at, or near, the original surface of the nucleus. (In Section 3 below we argue that sublimational erosion is unlikely to have removed more than the top few layers from the original nucleus since the time when it entered the inner Solar System.) From visual inspection, the scarps bound the superposition of one layer upon another. Both Thomas et al. (2007) and Veverka et al. (2006) present further evidence of layering on sloping topography near (30 W, 0) remarking: "At least three layers have exposures 10 to 250 m in width and appear to be steeply dipping relative to the surface over more than 3 km in length." Except in the case of regions a, b, and e, layer boundaries are not well defined because of the lack of imaging coverage. The area covered by each of these three regions can be estimated using the shape model and we find 1.9, 2.1, and 4.0 km^2, respectively, with an uncertainty of $\pm 10\%$. The extent to which the boundaries of these layers might have receded due to sublimational erosion following the comet's arrival in the inner Solar System is unknown and so these estimates should be viewed as minimum values for the original layer before the onset of sublimational erosion. In order to be specific we take as our estimate of the area originally covered by a typical layer at or near the surface as 5 km^2 while recognizing that a range of layer areas surely exists. It is possible that a considerably larger numerical value might be appropriate for the average area covered by a layer. Nevertheless, and for reasons that will soon become apparent, we do not think that these layers were at one time global in extent, i.e., we are not dealing with a phenomenon where the original structure was as in an onion.

The heights of the bounding scarps cannot be measured with great accuracy, although stereoscopic views and shadows clearly indicate the magnitude and sense of vertical relief. The boundary scarp between regions c and d is estimated at a few meters, while that between a and c is a few tens of meters. The vertical relief between g and e is estimated at $\sim$100 m. The latter estimate is similar to the vertical relief of $\sim$100 m seen at lower spatial resolution on Borrelly (Britt et al., 2004) and Wild 2 (Brownlee et al., 2004). To define the characteristics of a typical layer on the surface of Tempel 1 we shall assume a typical vertical relief of 50 m and an area of 5 km^2. These values imply that the volume of a typical layer at the surface is $2.5 \times 10^8\ \mathrm{m}^3$ and its mass 10^{11} kg using the bulk density of $400\ \mathrm{kg\,m}^{-3}$ as determined by Richardson and Melosh (2006). This volume is equivalent to that of a sphere of radius 390 m at the same density, a fact that will be of interest when we discuss the nucleus accumulation process. Table 1 summarizes some relevant properties of the nucleus and the observed and inferred properties of cometary layers. According to our hypothesis the nucleus interior could be composed of hundreds of

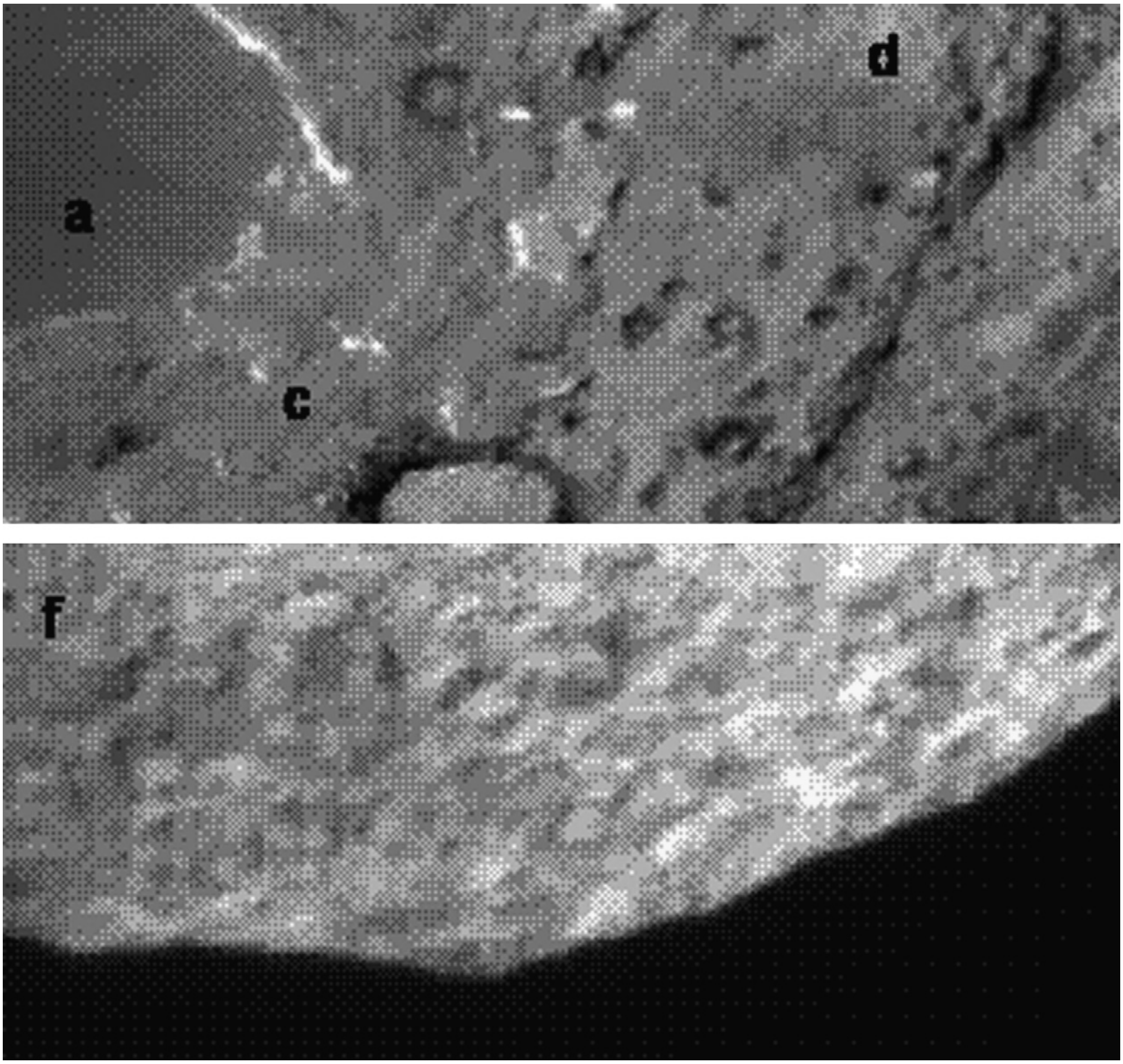

Fig. 3. Expanded view of the surface texture of some of the layers identified in Fig. 2.

such layers and tens of layers should be visible over the entire surface.

Thomas et al. (2007) provide a complete description of the geology of the surface including that of several layers. For completeness we repeat some of the salient points and add others. Two of the layers (*a* and *b*) are extremely smooth (i.e., they show few, if any, contrasty surface markings at this spatial resolution). One of them (*a*) shows faint markings indicative of flow (Fig. 3). Both appear to be channeled in topographic lows. Thomas et al. argue that layers *a* and *b* may be young, the result of recent geological activity. Here, in concert with our hypothesis, we will assume that these layers are simply part of a general class of features that have a common origin and seek to explain their varied characteristics in terms of processes that apply to all layers. Regions *c* and *d* (Fig. 3), separated by a low scarp, have different characteristics; region *c* is moderately rough and peppered with slightly higher albedo spots (one of which appears to show signs of sublimational activity) and has few, if any, "craters." Area *d* has the same underlying texture as *c* but is characterized by quasi-circular dark markings which we presume to be the remnants of impact craters. It shows few, if any, higher albedo spots, and the remnants of the two prominent impact craters near (0 W, 25 S) and (345 W, 28 S) appear to be contained within it. The texture of area *f*, perhaps the most complex on the surface, has a mottled appearance and has visual similarities to the mottled terrain seen on Borrelly by Britt et al. (2004), which they characterized as rough with "... depressions, troughs, hills and ridges." However, the presence of such details in the Deep Impact pictures is not obvious although there are hints of some circular features. Area *f* appears to have a photometric roughness twice of the global average based on the shape model of Tempel 1 (Li et al., 2006). The color ratio maps shows very subtle color variations on the surface, that are correlated with the layers identified here.

Table 1
Some relevant properties of the nucleus of 9P/Tempel 1 and the layers seen on its surface

Property	Value/comment
Surface area of nucleus	124 km^2
Volume of the nucleus	118 km^3
Mass of nucleus	$\sim 5 \times 10^{13}$ kg
Area of typical layer	$\sim 5\ \text{km}^2$
Thickness of typical layer	∼50 m
Volume of typical layer	$\sim 2.5 \times 10^8\ \text{m}^3$
Mass (density = 400 kg/m^3)	$\sim 10^{11}$ kg
Equivalent number of layers	∼500
Layers to cover surface	∼25
Types of layers from surface texture	1. Smooth with faint flow lines $[a, b]$ 2. Moderately rough peppered with brighter spots $[c]$ 3. Rough with mottled texture $[f]$ 4. Moderately rough with dark circular features (impact craters?) $[d]$
Composition	Varied H_2O and CO_2 content

Note. The identification scheme for types of layers refers to Fig. 2.

There are two other aspects of the surface that reflect on the basic compositional properties of the layers. These are the discrete areas of enhanced water ice (Sunshine et al., 2006) near (80 W, 10 S) and (100 W, 10 N), the enhanced CO_2/H_2O ratios in the inner coma over the South Polar Region (Feaga et al., 2006), and enhanced activity around the South Pole (Farnham et al., 2007). Evidently, if our hypothesis is valid, cometary layers must have some compositional diversity, or there is some special, as yet unidentified, process at work that locally enhances water ice and CO_2 content.

3. The relationship of the layers to the physical and dynamical evolution of cometary nuclei

Our hypothesis views layers as the basic structural element of the nucleus interior and so to understand them we must pay particular attention to the process of accumulation, i.e., what happens when fractal aggregates collide and what internal processes might occur as they grow? [For a review of early ideas on this topic see Donn (1991).] There are other processes that occur early, e.g., radioactive heating and any associated water ice phase change, that could induce global stratification in the interior but the characteristics of these processes are such that they would not be expected to create discrete layers near the surface of a ∼3-km-radius nucleus. For example, radioactive heating, which mainly affects the phase of water ice in the center of the growing nucleus, is not expected to have significant effect in bodies less than 50 km in radius (Prialnik et al., 2004). Late in the evolution of a comet nucleus, a water ice crystallization front is expected to propagate from the surface into the interior due to solar heating. This process has been suggested as the energy source of outbursts observed to occur at large heliocentric distance (see Prialnik et al., 2004, for a review). However, it seems unlikely that this process would also lead to layers in the near surface that have the kind of different geologic textures that are observed and described in Section 2.

After the nucleus is mature, i.e., the accumulation process ceases, it has a long period (∼4 Gyr) of post accumulation dynamical and environmental evolution and we must consider what effects this have on the proposed layer structure.

Finally, we must consider what happens to the layers in more recent times after the nucleus has moved into the environment of the inner Solar System.

The literature on these issues is large and it is not our intention to provide a critical overview or appraisal in this short contribution. Instead, we use the paradigm that emerges from chapters in the recently published *Comets II* (Festou et al., 2004) and *Protostars and Planets IV* (Mannings et al., 2000) books as a guide. In particular we rely on Weidenschilling (2004) for insight into the agglomeration phase, Farinella et al. (2000) and Morbidelli and Brown (2004) for post accumulation evolution of cometary nuclei in the Kuiper belt, Duncan et al. (2004) for insight into the dynamical evolution of Jupiter family comets, and Meech and Svoren (2004), Jewitt (2004), and Prialnik et al. (2004) for insight into their physical evolution in the inner Solar System. Since these authors provide a rich source of references to original work, primary references will only be used in special cases.

3.1. The accumulation stage

According to the models of Weidenschilling (1997, 2004) the accumulation of cometary sized bodies in the outer solar nebula near 30 AU should occur very rapidly. (It is not known where most JFC cometary nuclei are actually accumulated and 30 AU is simply a conjecture: it is cold enough to accumulate volatiles like CO and yet near enough to the forming Neptune to allow cometary nuclei to become member of either the scattered disk or the classical Kuiper belt.) After $\sim 10^4$ yr the mid-plane of the nebula is populated with microscopic fractal-like aggregates and by 2.5×10^5 yr bodies of ∼10 km size have grown (in these studies size is equivalent to an effective diameter). The model size distribution is roughly a power law below 1 m. There is a marked deficiency of objects between 1 and 100 m that is the result of the rapid build up of larger objects. After 2.5×10^5 yr most of the mass falls in the ∼100 m–10 km size range. Inward migration of growing trans-neptunian objects also occurs in the nebula, mainly in the size range 0.1–10 m, and this affects their radial distribution and, possibly, their composition.

At this point a new phase in the dynamics of this region sets in response to: (a) an increase in effective collisional cross-section of the largest objects due to their self-gravity that causes gravitational stirring and (b) to the growing gravitational influence and orbital migration (Fernandez and Ip, 1984) of Neptune. Detailed modeling (e.g., Greenberg et al., 1984; Kenyon and Luu, 1998, 1999a, 1999b) shows that runaway growth should occur leading to the formation of objects as large as Pluto in 10^7–10^8 yr. The models of Kenyon and Luu (1999b) with fragmentation also show that currently accepted collisional fragmentation schemes ensure that objects ∼1-km-radius (and smaller) will be dominated by collisional fragments.

3.2. *The accumulation process and formation of layers*

Weidenschilling's model shows that most agglomerative collisions occur between aggregates of very different size and it is this factor that promotes growth. At center of this activity is the impact accumulation *process* itself. Weidenschilling (1997) assumes that at the small impact speeds that apply in the primordial nebula the mass of the smaller body simply adds to the larger at impact. (He does, however, include built-in impact energy scaled inefficiency so that the most energetic collisions that do not result in shattering of the target cause a loss of 10% of the targets mass through a "cratering-like" process. At larger impact energies complete shattering can occur.) With this kind of "asteroidal" impact modeling a "primordial rubble pile" structure (Weissman, 1986) for cometary nuclei is ultimately the natural outcome rather than the order that is seen in the observed layers.

There are, however, alternatives to this scenario. Donn (1990, 1991) has long ago pointed that cometary nuclei cannot have undergone an energetic collisional history and that growth by the accumulation of low density fractal aggregates that gently interpenetrate, compact, and adhere is required if comet nuclei are to retain their volatiles. More recently Sirono and Greenberg (2000) have pointed out that deformation and compaction are likely to be the dominant processes for impacts between fractal aggregates and that the result of the accumulation process may be neither rubble piles nor aggregates held together by gravity.

In their analysis, which depends considerably on the calculations of Dominik and Tielens (1997), at small impact velocities some of the colliding aggregates might simply bounce. At a somewhat higher velocities the pressure induced at the interface exceeds the compressive strength of the material and large scale compression, deformation, and interlocking occurs. At still higher relative velocities fragmentation of the impacting aggregate can occur and at some point cratering may set in. Sirono and Greenberg do not speculate on the nature of the deformation that they have in mind but we can gain some insight from the laboratory experiments of Wurm et al. (2005) were the outcomes of collision between dust aggregates at velocities up to 25 m/s are followed. Wurm et al. report that up to 13 m/s their aggregates rebound with a small degree of fragmentation, while at higher collision velocities (up to 25 m/s) about half of the projectile sticks to the target surface as a pile of fragmented dust and the remainder is ejected at low angles from the impact site.

The figures in Wurm et al.'s paper show that the ejecta surges as a cloud of fragments that move out in all direction on trajectories that are close to the horizontal surface of the target. Wurm et al. report that the ejecta velocities are much lower than the collision velocity. This result is reminiscent of the early impact experiments of Hartmann (1985) into powdered (weak) materials. He also found low ejecta velocities even for impact velocities as high as 2 km/s.

Table 2
Codification of the impact process for colliding fractal aggregates

Collision velocity (V)	Physical situation	Outcome
$V < V_e$	$P_{impact} < \sigma_c$	Rebound, some fragmentation
$V_e < V < V_{s1}$	$\sigma_c < P_{impact} < T$	Modest fragmentation, strong distortion (projectile squashed onto surface with some penetration)
$V_{s1} < V < V_s$	$\sigma_c < T < P_{impact}$	Fragmentation of smaller aggregate that sticks to the target with some compaction and the formation of low velocity ejecta blanket layer
$V > V_s$	$P_{impact} \gg T > \sigma_c$	Complete fragmentation of projectile and transition to a hypersonic cratering process

Note. P_{impact} is the pressure generated between the projectile and the target aggregate as a result of the collision. V_e depends on the compressive strength σ_c and V_s will reflect the tensile strength T of the aggregate. The values of these parameters are not known a priori for aggregates in the outer solar nebula but for porous aggregates Sirono and Greenberg find that $\sigma_c \ll T$. The experiments of Wurm et al. (2005) and the calculations of Weidenschilling (1997) suggest that $V_e \sim 1$–10 m/s. V_s is the velocity of sound in the porous aggregate and is likely to be ∼100 m/s. V_{s1}, which is the velocity at which fragmentation sets in, is unknown. The role of internal friction is not codified here but will presumably be significant in determining the geometrical form of the distortion and the onset of fragmentation.

In the context of our hypothesis the work of Sirono and Greenberg and of Wurm et al. taken together suggest that the impact process might be codified as indicated in Table 2 where, over a range of impact velocity, various types of layers might be formed as a result of a distortion and low velocity fragmentation of the impacting aggregate. Presumably, the introduction of this modification of the impact process into the simulations of the growth of cometesimals by Weidenschilling (1997, 2004) would not change the general results on formation timescales. Only our view of the structure of the forming cometary nuclei would change. In Table 2 the critical impact velocities V_e, V_{s1}, and V_s are not known a priori. However, Sirono and Greenberg have made some estimates of the compressive and tensile strengths that might apply and find that the compressive strength σ_c should be much less than the tensile strength T for porous aggregates. On collision substantial distortion might occur before fragmentation. To explain what is observed on Tempel 1, the final outcome would need to achieve an aspect ratio (width/thickness) of ∼20, which would presumably require fragmentation of the impacting aggregate to occur. We associate V_s with the sound velocity in the porous aggregate that, to an order of magnitude, is probably near 100 m/s. V_e is probably in the range 1–10 m/s using Wurm et al.'s experiments and Weidenschilling's calculations as a guide. The magnitude of V_{s1}, which governs the transition from deformation to fragmentation, is a matter of conjecture. The use of the asteroidal model for the outcomes of collisions in the outer Solar System does not model these effects and a more realistic model that builds on the ideas of Sirono and Greenberg (2000) and the experiments of Wurm et al. (2005) should, perhaps, be used instead.

To summarize, the incoming aggregates either bounce inelastically or are squashed into an ill-defined layer onto the surface of the target or are fragmented and laid down as an ejecta layer on the surface or, depending on the energy of the collision, are completely disintegrated possibly forming a crater. For the dominant range of impact energy, our hypothesis requires that the incoming aggregate first distorts then ultimately fragments to form a layer with the above aspect ratio. In Weidenschilling's (1997) modeling a 6-km-diameter cometesimal, roughly the size of Tempel 1, is growing by accumulating objects with a model diameter of ∼1 km at an impact speed of ∼200 cm/s. The volume of such an impactor corresponds, within a factor of two, to the volume to the typical layer listed in Table 1.

For hypersonic impacts, where complete fragmentation of the projectile aggregate and cratering should occur, a blanket layer might also be formed due to a basal surge that results from the gravity-collapse of a vertical plume (Schultz, 2003). After the impact on 9P/Tempel 1 ejecta was observed still falling back over the impact site an hour after the event. Unfortunately, it was not possible to observe the resulting distribution of material on the surface with the Deep Impact cameras. This presents an obvious goal for any future mission to this comet.

3.3. The dynamical history of 9P/Tempel 1 and its long-term collisional environment

While it is impossible to know the precise orbital history of Tempel 1, we can get an approximate idea of its probable history by tracing the dynamical behavior of a typical JFC that has now reached the inner Solar System. Duncan and Levison (1997), Duncan et al. (2004), and Morbidelli and Brown (2004) provide us with information on current ideas. We can assume that the object we now know as Tempel 1 was born somewhere in the outer proto-planetary disk outside of the orbit of what was to become Neptune and then, following the formation of the planet found itself as part of the scattered disk. Here it spent a great deal of time, ∼4 Gyr, on various orbits moderated by occasional approaches to Neptune. Eventually, a particular encounter with Neptune occurred, perhaps 10^7–10^8 yr ago, that lowered its perihelion distance to the vicinity of Uranus and it began a journey that would bring it, via the succeeding gravitational influences of Saturn and Jupiter, to near its present orbit. Here it moves between various orbits with perihelia below and above 2.5 AU (a somewhat arbitrary distance used by Duncan et al. to distinguish between orbits where the comet is active or not), enjoying at times periods of relative stability, until, after about 3×10^5 yr from now, it will find itself on an orbit that will likely take it out of the Solar System. During its time near the Sun it will have spent ∼7% (Duncan et al., 2004) of its time on orbits that cause it to become active near perihelion and undergo sublimational erosion at its surface. It is presumably sometime during this last period of its life that the Deep Impact mission reached the comet and observed the layer structures on its surface.

During this journey there are two periods in which the layers, put down in the accumulation phase, could have been perturbed. The first is during its long stay in the Kuiper belt and/or scattered disk regions when collisions with the vast number of objects there in the early days of Solar System history (Stern, 1995) could have disturbed the layer structure. The second is during its time close to the Sun when sublimational erosion severely perturbs the outermost layers. We consider each of these evolutionary periods in turn.

The collisional environment in the cometary accumulation zone is thought to have changed dramatically with the formation of Neptune ∼10^8 yr after the birth of the solar nebula (Fernandez and Ip, 1984; but see Levison and Stewart, 2001). Neptune's gravitational influence is thought to have stirred up the eccentricities of the newly accumulated Kuiper belt objects leading to a violent collisional regime in what, according to Stern (1995), must have been a much more massive Kuiper belt than exists today. According to Farinella et al. (2000) and Durda and Stern (2000) it is likely that by the time ∼4 Gyr later when Tempel 1 moved onto the orbit that would take it to the inner Solar System it would have already been transformed into a rubble pile. In the current paradigm the vast majority of 1–10-km objects in the Kuiper belt are expected to be collisional fragments or rubble piles. Perhaps only 1 in 10 of the 10-km objects is estimated to have survived from the accumulation phase relatively intact and these would have heavily cratered surfaces. Durda and Stern estimate that after 3.5 Gyr a Kuiper belt object 2 km in diameter will have ∼20% of its surface covered by craters caused by impacts with 8-m-size projectiles.

Given this scenario it seems unlikely to us that all three Jupiter family comets that we have chosen to image could have come from the minority population of survivors, i.e., those objects that have escaped being transformed into rubble piles. Neither would we expect them to have escaped having extensively cratered surfaces. Tempel 1, Borrelly, and Wild 2 are more likely to have come from the collisionally evolved population. So either this scenario is inappropriate, or, in the context of our hypothesis, some process must operate to protect the layer structure from the effects of disruptive collisions. Further, a second process must operate that can eradicate pervasive signs of cratering. Even if the layers can survive the fragmentation process, the randomly oriented coalescence of the fragments to form rubble piles would surely obscure evidence of layering on a global scale. Only if the same process that led to layers in the accumulation phase still applied would layers persist. Thus in the creation of a rubble pile a new system of layers might be built up and we have something that might be called a second generation "layer pile." These layers would not be talps since they would no longer be primordial.

To remove evidence of impact craters an erosional process operating at the surface is required. Possibilities include sublimational erosion due to sunlight after the comet has arrived in the inner Solar System, or to a high fluence of appropriately energetic micrometeoroids (we thank J.A. Fernandez for this latter suggestion). These processes, including the impacts themselves, would be expected to operate over the entire surface. However, the observations seem to tell a different story. On the surface of Tempel 1 only layer *d* in Fig. 2 shows obvious evidence of a proliferation of craters remnants; there is also small region between *f* and *g* where marginal evidence of craters exists. Layer *g* has three ∼100-m-diameter quasi-circular features near (20 W, 10 N) but it is not obvious from their morphology that they are the remnants of impact craters

(Thomas et al., 2007). Certainly craters, or their remnants, are not ubiquitous and where they do exist their surface density is low (Thomas et al., 2007). We conclude that either the Jupiter family comets found a way to avoid the collisional regime described by Farinella et al. (2000) and Durda and Stern (2000) or the collisional outcomes were different to what they describe.

A process that might allow the newly accumulated cometary nuclei to avoid a long collisional evolution is one that was identified by Duncan and Levison (1997). They suggest that some primordial objects are channeled into a scattered disk as a result of close encounters with the forming or newly formed Neptune. While the collisional environment of scattered disk objects has not, to our knowledge, been worked out quantitatively we presume with Rickman (2004) that the larger perihelia, eccentricities, and inclinations of objects in the scattered disk (Morbidelli et al., 2004) leads to a far more benign collisional environment than in the compact Kuiper belt with which it partially overlaps. In this way, comet nuclei might be accumulated and their primordial surfaces and interiors preserved. A problem with this scenario is the long estimated timescale for the formation of Neptune which, at a few times 10^8 yr (Fernandez and Ip, 1984; Levison and Stewart, 2001), suggests that the newly accumulated comet nuclei could have been collisionally compromised long before Neptune could channel them to the scattered disk.

If our hypothesis is to make some sense it seems likely that the modeling of fragmentation outcomes in the outer Solar System needs to be reconsidered. For example, if collisions produce only fine dust and no large fragments (we note that this may have been the case for the artificial impact at Tempel 1), rubble piles will not form and surviving objects in the 1–10 km range will retain the internal structure that was laid down in the early accumulation phase. The calculations of Davis and Farinella (1997) give some insight into this as their collisional evolution calculations show that as the impacting particles are assumed to become weaker and less elastic the surviving population remains dominant to smaller sizes.

3.4. *The effects of sublimational erosion near the Sun*

At present Tempel 1 undergoes mass loss of 6.8×10^8 kg of dust per orbit (Lisse, 2002) and the gas loss is presumably at a similar rate. Dust-to-gas mass ratios in comets are difficult to pin down but are thought to be >1 (Fulle, 2004). Thus a mass loss rate of 10^9 kg per orbit is a conservative estimate for the present epoch. This estimate is in line with the range of $5 < Q < 10^2$ kg/s for low activity comets near perihelion in cited by Meech and Svoren (2004). It should be noted that this is not a smooth process, Jupiter family comets show stochastic variations in mass loss rate from perihelion to perihelion and evidence for a factor of two is common. [This has actually been the case for Tempel 1 during its last two perihelion passages (A'Hearn, personal communication).]

There appears to be no convincing evidence for long-term secular fading in Jupiter family comets and Meech and Svoren (2004) conclude that "If comets do fade, they do so very slowly ...." The fading seen in the Oort cloud comets (Dones et al., 2004) appears to be an unrelated problem. With these caveats, we assume that Tempel 1 has lost on average $\sim 10^9$ kg per orbit during the entirety of its active lifetime. This should be a conservative posture for calculating the integrated mass loss since it entered the inner Solar System.

To estimate the number of active orbits that Tempel 1 (or Borrelly or Wild 2 which have similar mass loss rates) has experienced we suppose, for lack of any evidence to the contrary, that it is mid way through its "physical" lifetime of between 3000 and 25,000 yr (Duncan et al., 2004). Thus we estimate that Tempel 1 might already have experienced anywhere from 200 to 2000 active orbits as a Jupiter family comet (an orbital period of 6.8 yr, the average over the last 26 apparitions, was used in this calculation). It has therefore lost a total of between 2×10^{11} and 2×10^{12} kg of its original mass. Referring to Table 1 this corresponds to $\sim$2–20 of the typical layers now seen on the comets surface. From the point of view of sublimational mass loss, the nucleus of 9P/Tempel 1 should be much as it was when it left the vicinity of the Kuiper belt $\sim 10^7$ yr earlier but with probable partial loss of the original top layers which in specific areas may have lead to the exhumation of those immediately below.

3.5. *Other evolutionary effects*

There is a long list (Stern, 2003) of other evolutionary processes that will effect the condition of the original outer layers, not least the formation of a lag deposit and compositional stratification as a by product of sublimational evolution (Prialnik et al., 2004). These can lead to stratification of properties in the upper $\sim$10 m of the surface but are not expected to produce effects of comparable scale to those discussed here. There is also the possibility noted earlier of radioactive heating and phase changes affecting the structure of the deep interior. These are discussed by Stern (2003), Meech and Svoren (2004), and Prialnik et al. (2004) and will not be considered further here.

4. The talps or "layered pile" model

Examination of our hypothesis that the layering seen on the surface of Tempel 1 *is ubiquitous on Jupiter family cometary nuclei and is an essential element of their internal structure* plus examination of the observational characteristics of these layers and the comet's likely evolutionary history leads us to the following conclusions:

1. The rubble pile model, either collisionally modified or primordial, does not represent what is observed satisfactorily.
2. The observed layering on the surface of Tempel 1 was likely formed during the accumulation phase as a result of gentle agglomerative collisions and are present in the interior of the nucleus.
3. Details of the accumulation process particularly the mode of distortion and fragmentation of the impacting aggregate need further investigation along lines suggested by Donn (1991), Sirono and Greenberg (2000), and the experiments of Wurm et al. (2005).

4. The order implied in the observed layers and the lack of extensive cratering over the surface indicate that they have not seen the kind of collisional environment that current Kuiper belt models employ. The outcome of collisional fragmentation maybe different from what has been assumed.
5. If Jupiter family comets originated in the scattered disk then the environment there must be collisionally benign or the collisional fragmentation model requires modification.
6. The original surface of Tempel 1 may have been largely removed by sublimation leading to partial exhumation of layers below the original surface.
7. The observed layers have themselves been substantially modified by sublimational erosion.

To test our hypothesis further a new model for the interior is needed. A schematic of our proposed model, which we call the "talps" or "layer pile" model, is shown in Fig. 4. Talps is our name for *primordial* layers to distinguish them from other layers that might exist and have a more recent geological origin (see below). We propose a basic structure that consists of a central core of material on which is superposed a randomly placed stack of layers that on the average increase in volume, thickness, and lateral extent as the surface is approached. The core, whose extent is not known (with the exception that it should be relatively small), contains the original aggregate that initiated the growth of the comet. It is distinct from the layered regions accumulated later because it is thought to form from fractal aggregates that gently interpenetrate, compress and minimally distort much in the way described by Donn (1990, 1991).

The transition to the layered region begins when the incoming aggregates begin to distort and fragment on to the surface. The reason why they, on the average, increase in volume, thickness, and lateral extent as the object grows follows from details of Weidenschilling's (1997) model: The accumulation of the aggregates takes place primarily at low relative velocities, presumably well below the velocity of sound (~100 m/s) and is primarily the result of collisions with objects that are much smaller than the target. As the bodies increase in size, the median size of the colliding aggregates is found to get larger and the impact velocity decreases. Weidenschilling (1997) finds that by 2×10^5 yr the largest bodies, ~6 km in size, roughly the size of the nucleus of Tempel 1, are accreting objects with a modal diameter of ~1 km at remarkably low impact velocities of ~2 m/s. With 100% efficiency such an impact could produce a layer, assumed 50 m thick, with an area ~10 km^2 only twice as big as the typical layer estimated in Table 1. In this scenario the early layers would be much smaller (because the modal size of the impacting aggregates is smaller) and more compact (because of the higher impact velocity) than the later ones and so we should expect there to be a gradual thickening of the layers as the accumulation proceeds.

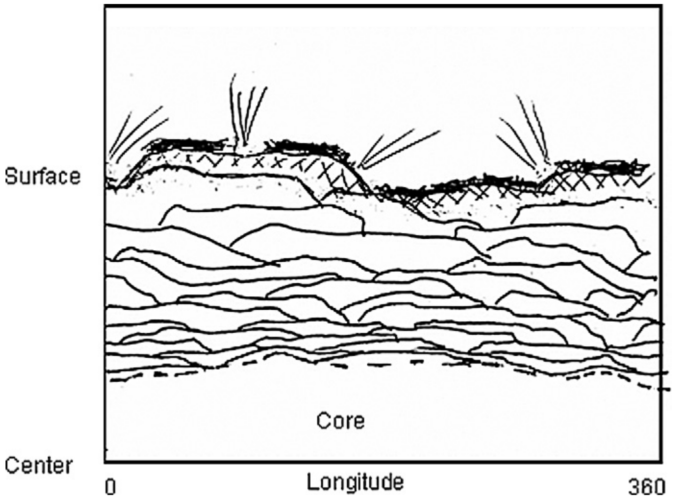

Fig. 4. Cartoon of the "talps" or "layered pile" model for the interior of Jupiter family cometary nuclei. The plane of the picture is in the equatorial plane from the center of the comet to the surface. The distance from the center to the surface is an arbitrary scale. At the center is an ill-defined core which represents the original aggregate that initiated the growth of the nucleus. The primordial layers, or "talps" that were laid down as a randomly place stack in the first 10^6 yr of the accumulation period increase in lateral dimension and thickness as they approach the surface. The top layers are partially modified by solar radiation and covered with a broken lag layer. Activity can occur either on the surface of the outermost layers or at the scarps that define its boundary.

The question arises as to whether the inner layers might become compressed, perhaps beyond recognition, by the weight of the overlying layers? If something close to hydrostatic equilibrium applies then the central pressure of a 10-km-sized object with a density of 400 kg/m^2 can be estimated with the expression GM^2/R^4 (Hubbard, 1984; G is the gravitational constant, M and R are the mass and radius of the nucleus); we find a central pressure of $\sim 5 \times 10^3$ dynes/cm^2. Sirono and Greenberg (2000) estimate a compressive strength of $\sim 10^5$ dynes/cm^2 for a porosity of 0.3 and so severe compression due to the weight of the overlying material is not expected for cometary nuclei. For this reason the mass distribution is expected to be essentially homogeneous, i.e., there should be no appreciable increase in density towards the center.

4.1. *Does this model provide a reasonable explanation for what is seen at Tempel 1?*

The gross properties of the outer layers (Table 1) are approximately explained in terms of the mean size of the colliding aggregates near the termination of the growth of the newly formed nucleus as explained above. The range in thicknesses is a result of the stochastic nature of the accumulation process and the range in impactor size. Evidence for flow seen on the smooth layers and their location in gravitational potential lows could simply be a reflection of channeling of a slowly moving ejecta flow by the local topography. The presence of craters on some layers and not on others and the difference in texture from one layer to another might be explained by different exposure times to the environment during the accumulation process. In the $\sim 10^5$–10^6 yr that it took to accumulate the nucleus perhaps ~500 major layers were added to the nucleus. This would imply that, except for the surface layers, a mean exposure age of 5000–50,000 yr per layer to the environment if it takes the deposition of ~25 layers to cover the surface at any particular time. Whatever the actual mean exposure time the deposition of layers is a random process and each layer will experience a different exposure time dispersed around the mean exposure time. Some layers will have short exposure times being buried quickly and so avoid the formation of craters and modification by the environment, others will see the environment for extended times and undergo surface environmental modification and accumulate a few cratering events. In this way we might explain the diversity of surface textures seen in the images.

The existence of regions of enhanced water ice and CO_2 requires a more complex explanation. Weidenschilling (2004) reports that his two-dimensional model shows inward migration of solid material from the outer parts of his model nebula as meter-sized bodies are rapidly accumulated onto larger bodies in the inner regions. If compositional inhomogeneities exist on the scale of a few AU in the nebula this could offer a possible explanation.

4.2. *Other cometary phenomena*

The phenomena of splitting and outbursts may be related to one another as well as to the compositional differences already noted. Fragments that are released during a random splitting event appear to be typically sub-kilometer in size (Boehnhardt, 2004) and last for a few to several thousand days. Individual talps can provide a possible source for such fragments since we have already noted that the volume of a typical layer is equivalent to a 390-m-diameter object. The force required to remove a talp will depend upon the nature of the collision that created it (not all talps are necessarily alike). Sirono and Greenberg (2000) have pointed out that during the compression period there will be a certain amount of interpenetration and interlocking and that merged aggregates will have strength above that which is expected on a strictly gravitational model. We propose that splitting occurs as a result of rotational (centrifugal) forces that overcome the *adhesion* of talps to the surface. Since the *e*-folding time for the spin rate of an active comet (Jewitt, 1997; Samarasinha et al., 1986) is very short (a few years) and there is bound to be a range of adhesion strengths, a particular comet nucleus could be stable for an indeterminate time and then unexpectedly split. This could reoccur in a particular comet many times in an unpredictable fashion depending on the precise properties of the talps.

Outbursts could have multiple physical causes in the talps model but presumably all related to a compositional inhomogeneity such as the local enhancement of a super volatile (e.g., CO_2, CO). The bright spots in region *c* could be evidence of such an enhancement since at least one appears to show contemporary signs of activity (P. Schultz, personal communication). Perhaps the most obvious physical situation would exist at a scarp boundary as sublimational backwasting of dust laden water ice reaches a local enhancement of a supervolatile. The backwasting reduces the local overburden or allows the volatile to feel the Sun and an outburst occurs.

5. Predictions and goals for future missions

The hypothesis that we have tested in this paper clearly has significant implications for our understanding of processes and the environment during the earliest phases of the development of the Solar System. However the ideas developed need further examination before we can be assured of their veracity. There is a need not only to visit new cometary targets but also to revisit comets that we have already encountered. There is an urgent need to revisit Tempel 1 to complete the survey of the surface and understand the layer structure in a more quantitative way. We need to explore the "other" side of this comet. An equally important objective is to examine the vicinity of the artificial crater that Deep Impact created. Quantitative knowledge of the ejecta blanket that was laid down should provide insight into how cometary material fragments in collisional events and help us to understand the processes that occurred in the accumulation phase. In addition close examination of the structure in the upper twenty meters that may available in the crater walls may place important constraints on how the evolution of the outmost layer proceeds in response to the Sun.

There is also a need to return to Borrelly and examine the interior structure of the nucleus in of the vicinity "narrow" end of the comet which seems to be an object fused to the main body of the comet perhaps as the result of a collision in primordial times. This could be done with a long wave penetrating radar experiment or a transmission experiment along the lines of the CONSERT experiment on ESA's Rosetta mission.

An aggressive exploration of the diversity exhibited by cometary nuclei is also called for. Our hypothesis was based on subtle similarities in what was observed by three missions with radically different observational capabilities. New objects need to be visited with enhanced capability to ensure that these similarities were not the result of chance.

The Rosetta mission with its powerful CONSERT radio tomography of the interior and its lander and remote sensing packages should be able to provide detailed information on any layering and compositional heterogeneity that is found (and which we predict).

Finally, there is clearly much theoretical modeling and laboratory work to be done. Models of KBO accumulation need to be considered with alternative fragmentation scenarios. The three-dimensional nature of impacts between weak, low density, aggregate bodies need investigation—both theoretical and in the laboratory. The collisional environment in the scattered disk needs to be better understood. A quantitative numerical model of the talps concept needs to be done.

The picture of interior structure that has been sketched out in this paper refers only to the Jupiter family comets. Long-period, or Halley type, comets are thought to have a different early evolutionary history and this may be reflected in their interiors. An ordered layered structure may not be the case here since their early history may have been more violent. Ultimately, comparative observations of JFC and Halley type interiors and surfaces are needed.

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