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The interior of outer Solar System bodies

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Abstract. The population of small bodies of the outer Solar System is composed by objects of different kind and size, such as comets, Kuiper Belt objects and Centaurs, all sharing however a common characteristic, that is to be rich in ices and other volatiles. The knowledge of the composition and properties of these bodies would help in better understanding the processes that shaped the solar nebula at large heliocentric distances and determined the formation and evolution of the planets. A large number of observational results are now available on these bodies, due to successful space missions and increasingly powerful telescopes, but all our instruments are unable to probe the interiors. However, we are beginning to see how these seemingly different populations are related to each other by dynamical and genetic relationships. In this paper we try to see what could be their thermal evolution and how and when it brings to their internal differentiation. In fact, in this way we can try to foresee what should be the surface expression of their differentiation and evolution and try to link the surface properties, as probed by instruments, with the interior properties. One thing to note about the cometary activity is that it is well interpreted when assuming that the comets are small, fragile, volatile-rich and low-density objects. This view, despite of the strong differences noted in the few comet nuclei observed in situ, has not been disproved. On the other side, the observations of the Kuiper belt objects are possibly indicating that they are large, probably collisionally evolved objects (Farinella & Davis 1996), maybe with larger densities. We are now facing a kind of paradox: we have from one side the comets, and from the other side a population of much denser and larger objects; we know that a dynamical link exists between them, but how can we go from one type of population to another? In this paper the current status of our knowledge on the subject is reviewed, taking into account the results of thermal modeling and the results of observations.

Keywords. comets: general, Kuiper Belt, planets and satellites: formation

1. Introduction

In this paper we analyze the internal structure of the small objects that originated in the outer solar system, beyond Neptune: Kuiper Belt objects (KBOs), Centaurs and short period comets.

All these bodies accreted from the protoplanetary nebula extending beyond the region where planets formed, but we do not know exactly where: in fact many of them were displaced and scattered from the accreting proto-Uranus and Neptune. In particular, the bodies that are now present in the Oort cloud are probably belonging to this category. It is also commonly accepted that the bodies populating the Kuiper Belt formed in a region roughly overlapping their present position. Moreover it has been suggested that the Kuiper Belt zone could be the source of most short period comets (Fernandez 1980). In this frame, Centaurs, with their instable orbits, represent bodies caught “on the way”.

From a physical point of view all these bodies, having been originated in the same place, should be closely related and should have the same intrinsic physical nature.

Obviously there are effects, related to the size of these bodies, that can finally lead to a different evolution, but we should be able to decipher their main evolutionary path and establish common genetic relationships. The small bodies present in the outer solar system are characterized by a high content of volatiles elements, that can lead under certain thermodynamic conditions to the development of an intrinsic activity, giving rise to the sublimation and loss of water ice and high-volatility carbon compounds. The properties of these bodies can be the result of the physical and chemical conditions prevailing in the solar nebula to the moment of their accretion and of the processes acting on them during the subsequent evolution. We know also that this region was characterized by a high degree of "mobility", as shown by Morbidelli (2004), that strongly influenced the subsequent history and hence the present structure and composition of many objects.

Lets now try to identify the region that we want to take into account: while the outer edge is obviously the Oort cloud, the in-bound edge is more difficult to define due to the fact that comets undergo a multistage capture process, and that they can be even scattered into the inner solar system eventually contributing to the Near Earth Objects population. For sake of simplicity we can consider the asteroid belt as the deeper inner edge.

The present structure and appearance of these bodies has been affected by their dynamical history, by the surface aging (reddening of surfaces due to irradiation), by their activity (when present, as in the case of comets) and by their collisional evolution. This last process, in particular, could have heavily shaped them: the comets could even be collisional fragments directly ejected from the Kuiper belt.

As far as the sizes are concerned, it is very difficult, after the discovery of several "minor bodies" of very large size like for example Varuna (Jewitt & Sheppard 2002) and 2003 UB313 (Brown 2005), to define a clear limit between them and the "real" planets. However, in this review we will not deal with planet-sized bodies, that probably underwent processes closer to the ones that shaped the planets than to the ones affecting small bodies.

The interior of these bodies cannot be directly probed, however we can at least infer their composition from the theories of protosolar nebula chemical evolution. Cosmogonical theories usually predict that the first condensates grow through different accumulation processes, that include low velocity mutual collisions. In the process of adhesion different parameters play important roles, affecting both the velocity and the mass distribution of grains. Among those affecting mainly the velocity distribution of particles, we have to mention gas turbulence and gas-dust drag forces, while the mass distribution depends not only on the relative particle velocity but also on their sticking efficiencies. The relative importance of gravitational instability with respect to collisional coagulation can have consequences on the final structure of the cometesimals and on the porosity of the resulting bodies. For this reason, density (porosity) is an observationally derived property having cosmogonical significance. We can obtain hints on the internal structure also from the modeling of the thermal evolution of ice-rich bodies, and from the new data collected both by planetary missions and by ground based observations of the different objects belonging to this category. In this paper we will try to combine the different sources of data and to see how they can be used to improve our theoretical approaches in order to create a general scheme.

After the previous, very general definitions, we will briefly discuss the objects included in our review from the point of view of what it is known about their interiors from observation; after that, we will discuss the hints that we can obtain from formation models and from thermal evolution models; then, we will try to reach some conclusions.

2. Kuiper Belt objects

After the discovery of the first Kuiper Belt object, the number of KBOs directly detected has greatly increased, as well as the area of the solar system in which they are found. The orbits of the so-called classical Kuiper Belt objects fall into two main categories (Luu & Jewitt 2002): objects with $a < 41$ AU and $e > 0.1$ (like Pluto and Charon) that are in mean motion resonances with Neptune and objects with $41 < a < 50$ AU and $e < 0.1$ (like 1992 QB1) that are not in resonant orbits. Another component of the trans-neptunian region, the so-called scattered Kuiper Belt, has been added in the last years: these objects are characterized by highly eccentric orbits extending to ~ 130 AU and could be planetesimals that were scattered out of the Uranus-Neptune region into eccentric orbits. It is probable that the Kuiper Belt could extend much farther than we know, and that some objects can be found up the Oort Cloud. In addition, many if not all of the so-called short-period comets (orbital periods < 200 years) likely had their origin in the Kuiper Belt, and represent the detectable (via proximity) subclass of what may be an enormous number of such bodies in the 30-100 AU region: the Kuiper Belt region should contain enough bodies to explain the observed rate of short period comets.

Jewitt (1999) argued that the inclination distribution of the trans-Neptunian objects is important because it controls the velocity dispersion of these objects and hence determines whether the collisional regime is erosive or agglomerative. The size distribution of KBOs is not well known, however it should be related to the primordial phases of solar system evolution, even if it was changed by the resonances and the progressive erosion due to different phenomena. The size distribution of a population of objects can be considered a useful diagnostic for understanding the processes that lead to the erosion and/or accretion of planetary bodies. From recent observations and theoretical studies, it is emerging that objects in the trans-neptunian region probably follow a complex size distribution. All the sizes are derived from brightness values and assume that the objects have an albedo of 0.09 (see Minor Planet Center, "Minor Planet Lists", on line, http://cfa-www.harvard.edu/iau/lists/MPLists.html, updated 19 August 2005). Thus, there are at least factor-of-two uncertainties in the estimates of the sizes of KBOs. On 28 July 2005, Santos-Sanz *et al.* (2005) announced the discovery of an object nearly as large as Pluto, now designated 2003 EL61. Brown, Trujillo & Rabinowicz (2005) reported, almost at the same time, the discovery of two large trans-neptunian bodies: 2003 UB313 is clearly larger than Pluto, based on its observed brightness, the other, designated 2005 FY9, is over half the diameter of Pluto.

Due to the distance and the consequent faintness of these objects, the observation is difficult: we have only lightcurves and low resolution spectra, from which we can have an idea of the surfaces. These surfaces are surprisingly different between them (Luu & Sheppard 2002), and probably heterogeneous. The observed color distribution could be attributed to the reddening due to irradiation and subsequent polymerization of the surface carbonized compounds and erosion activity/resurfacing. In this case, a transport mechanism able to bring fresh material on the surface is required.

Nothing we know about the interior of KBOs (and Centaurs), if not by extrapolation on what we know about the comets, which should originate from them. It is highly possible that the largest ones between the KBOs be in some way internally differentiated, due to the high content of refractory and hence of radioactive nuclei releasing heat in the whole nucleus, but the dividing line between objects large enough to be differentiated and those that should not is unknown. Collisions too could have had a role in thermally processing the interiors.

As far as the masses (and densities) are concerned we do not have data, with the exception of Varuna for which a density has been estimated (Jewitt & Sheppard 2002). Following the analysis of the lightcurve, the body could be a rotationally distorted rubble-pile, so it would be porous at an unknown scale and low density (~ 1000 kg/m^3). On the contrary, surprisingly, Jewitt & Luu (2004) discovered that Quaoar spectrum seems to indicate the presence on the surface of crystalline ice. Crystalline ice is formed only at temperatures above 110 K, well above the present temperature of Quaoar that, according with the previously cited authors, is about 50 K. The interpretation of this observation could be a strong indication of an interior activity of this large object leading to the generation of ice volcanism, similar to the one presently observed on Enceladus, or to the recent(?) exposition of the underneath layers of crystalline ice, being the first layers of amorphous ice removed by impact. Another possibility is that the ice on the surface could have been heated above 110 K by micrometeorite impacts. In the first case, the crystallinity could be an indication of the differentiation which the object undergoes, probably due to the combined effects of radioactive decay, primordial bombardment and compaction due to the body self-gravity. Therefore we cannot exclude that in some cases the large KBOs could resemble Triton more than a dead icy body.

However, the impact hypothesis cannot be excluded since the role of impacts in the Kuiper Belt has been relevant, as supported by the observation that the number of binaries is surprisingly high. The formation of binaries is explained by two competing theories. One entails the physical collision of bodies (Weidenschilling 2002) while the other utilizes dynamical friction or a third body to dissipate excess momentum and energy from the system (Goldreich, Lithwick & Sari 2002). In both cases the formation of multiple systems asks for a higher density of the KBO disk, that allowed the formation of binary and multiple bodies (Nazzario & Hyde 2005). This implies that the probability of collisions was higher than the present one. As noted by Funato, Makino, Hut *et al.* (2004) this will also allow direct mass determination in a near future.

It is to be stressed again that KBOs observation is indicating a contradictory situation: from one side the analysis of Varuna (Jewitt & Sheppard 2002) seems to indicate a porous interior, while the presence of crystalline ice on Quaoar spectrum seems to indicate a differentiation process, leading to compaction and differentiation.

3. Centaurs

A growing number of bodies, referred to as Centaurs, have been identified with orbits crossing those of Saturn, Uranus, and Neptune. These bodies can be seen as transition bodies between the KBOs and the comets (Levison & Duncan 1994, Hahn & Bailey 1990): the fact that their orbits, on the basis of dynamical calculations, are not stable over the lifetime of the solar system, suggests that the Centaurs were formerly residing in the Kuiper Belt and only recently have been delivered into their current orbits. The overall appearance, based on photometrical measurements, is also not in contrast with this hypothesis: the colour diversity and redness of the Centaurs match those of KBOs. This common origin with KBO makes the Centaurs very interesting, because they could provide compositional information on the more distant Kuiper Belt objects and information about their subsequent processing.

The estimated diameters are between 20 and 200 km, from Earth-based telescopic observations at thermal wavelengths and assuming low visual albedo. Three of these objects (Chiron, Pholus, and 1993 HA2) are large and bright enough for ground-based telescopic spectral observations at visual and near-infrared wavelengths (0.4 to 1.0 microns). Chiron

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(Hartmann *et al.* (1990); Meech & Belton 1990) and 5145 Pholus (Tegler, Romanishin, Consolmagno *et al.* (2005)) have independent assessments of their diameters. Chiron is a uniquely complex body, apparently undergoing sporadic outbursts of activity that may be driven by the sublimation of CO. Chiron has a flat reflectance spectrum similar to that of the C-type asteroids. Thermal-infrared observations suggest that its visual albedo appears to be low (0.04 to 0.1), further indicating a similarity to the C-type asteroids.

In marked contrast to Chiron's bluish colour, the visible reflectance of 5145 Pholus and 1993 HA2 is extremely red and exhibits steep upward slopes toward longer wavelengths. Unfortunately, the red slope alone is insufficient to identify a specific solid material; the presence of several distinctive absorption features has led to the hypothesis that the surface of Pholus is composed of a mixture of H_2O ice and a variety of organic materials. The organic materials suggested to date include light hydrocarbons or methanol ice, tholins similar to those hypothesized on Titan, polymeric HCN and carbon black. The presence of light hydrocarbons suggests that Pholus has been less chemically processed than comets and asteroids. Intriguingly, extrapolations of orbital calculations suggest that the current orbit is dynamically new and that Pholus may have arrived recently from the Kuiper Belt.

This is in agreement with the data recently collected by the VIMS Sperctrometer on the Cassini mission, that have found a complex chemistry on the surface of Phoebe. The origin of Phoebe, which is the outermost large satellite of Saturn, is of particular interest because its inclined, retrograde orbit suggests that it was gravitationally captured by Saturn, having accreted outside the region of the solar nebula in which Saturn formed. By contrast, Saturn's regular satellites (with prograde, low-inclination, circular orbits) probably accreted within the sub-nebula in which Saturn itself formed. The imaging spectroscopy of Phoebe shows ferrous-iron-bearing minerals, bound water, trapped CO_2, probable phyllosilicates, organics, nitriles and cyanide compounds. The detection of these compounds on Phoebe makes it one of the most compositionally diverse objects yet observed in our solar system. It is likely that Phoebe's surface contains primitive materials from the outer solar system, indicating a surface of cometary/KBO origin (Clark *et al.* (2004)).

An origin in the Kuiper Belt can probably also be assumed for a body such as Triton, and the identification of Pluto and Charon as the two largest known Kuiper Belt objects has been discussed (Cruikshank 2005). The identification of these large outer solar system bodies as KBOs provides a simple and consistent framework for their formation in the outer solar system: in this picture, Pluto and Triton formed in the trans-Neptunian region and became two of its largest members. Suggested capture mechanisms include a collision with an original satellite (Goldreich *et al.* (1989), or gas drag in a proto-Neptunian nebula (McKinnon & Leith 1995).

4. Comets

In the last years space missions such as Deep Space 1, Stardust and very recently Deep Impact gave us wonderful pictures of comet surfaces, but unfortunately they did not give us information on their interior structure. Most of our knowledge about comets is still based on the results of Giotto that studied the comet 1P/Halley in 1986, and on the data from two unusually active recent comets: C/1995 O1 (Hale-Bopp) and C/1996 B2 (Hyakutake). The imaged surfaces of 19P/Borrelly, 81P/Wild 2 and 9P/Tempel 1, all short period comets, are strikingly different each other, supporting the idea that, when looked from nearby, comets are diverse, probably due to the several paths that their internal evolution can follow only changing a few key parameters, such as the amount of volatiles and the presence or not of a refractory crust. Moreover there is a strict

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dependence of the comet evolution on the orbital path that it follows, and this evolution can deeply change its surface appearance (Coradini, Capaccioni, Capria *et al.* (1997a); Coradini, Capaccioni, Capria *et al.* (1997b)). We shall expect an even larger variability when we will be able to image the surface of a long period comet. Deep Impact, that successfully hit with a cupper projectile the nucleus of 9P/Tempel1, will possibly give us some hints at least about the composition of the layers close to the surface, when the analysis of the data will be completed. To the moment of this writing, there are no firm conclusions about the composition and density of these layers.

We have many ideas but not many constraints on the interior structure of cometary nuclei. What little we know about the interior of comet nuclei is inferred from observations and from our limited knowledge of the way in which comets accreted in the protoplanetary nebula, although we should keep in mind that the behavior could be history dependent and that the abundance ratio of ejected volatiles in the coma does not represent the nucleus abundances (Huebner & Benkhoff 1999). The Jupiter Family comets originated in the zone of the solar system presently known as Kuiper Belt and were successively scattered closer to the Sun, so they should have been formed in a colder environment with respect to the long period comets, but it is still unclear if this can bring any difference in their composition and properties. Whereas the cometary surface and the layers immediately behind are somewhat processed during each perihelion passage, the interior could be much more primordial. It is well possible that most nuclei are not homogeneous bodies: chemical and physical inhomogeneities should be present as a consequence of formation conditions and differentiation processes. Compositional differences could exist between the various populations of comets depending on their formation zone and subsequent processing. Even if a comet is born or find itself, at some stage of its existence, relatively homogeneous from a compositional point of view, thermal evolution will soon change this situation: diurnal heat wave penetrates for few centimeters under the surface, but seasonal and orbital heat waves penetrate much more deeply, depending on the thermal properties of the local matter.

As already written, we know something more about comets interior, in particular about density, than about the interior of the other bodies that are the subject of this review. In what follows we will review what we know about the porosity and density of comet nuclei.

4.1. *Comets are porous and low density objects*

It is usually assumed, both in interpreting observations and in modeling the evolution of nuclei, that comet nuclei are porous, low-density objects. The reasons for which we assume that comet matter is porous have been listed by Benz & Asphaug (1999): 1) It would be impossible to sustain the observed sublimation of volatile ices if only the volatiles present on a surface layer would be sublimating; 2) The analysis of non-gravitational forces acting on comet 1P/Halley indicated that the mass of the comet nucleus must be less than the mass of that body if it consisted of compacted material. The resulting density indicates that the nucleus is porous. 3) The material created during KOSI experiments (Laemmerzahl, Gebhard, Gruen *et al.* (1995)) was very porous; CO_2 gas was released from under the surface and diffused through the pores into the vacuum surrounding the experiment. To this list, it could be added that nucleus models explain very well comet activity assuming that gas diffusion is taking place in a porous medium (see section 6).

The bulk density is one of the most elusive, yet important, physical properties of a cometary nucleus. The methods that can be used for mass or bulk density estimates are mainly based on tidal or rotational break-up and non-gravitational force modeling. For example, it is possible to utilize the fact that a body needs a certain self-gravity and material strength in order to withstand the centrifugal force due to rotation. Davidsson (2001) derived analytical expressions for the critical break-up period, by assuming oblate or prolate nucleus shapes, and by balancing gravitational, material, and centrifugal forces. If the size, shape, and rotational period of a comet are estimated observationally, these expressions can be used to derive a lower limit on the density. An interesting attempt to obtain hints on the density of real bodies has been made by Davidsson & Gutierrez (2004) and 2005)by Davidsson & Gutierrez (2004). By requiring that the model body simultaneously reproduces the empirical nucleus rotational lightcurve, the water production rate and in particular the non-gravitational changes induced on the orbital parameters, the authors are able to estimate the density of the nucleus. In the case of 67P/Churyumov-Gerasimenko they obtain a value ranging from 100 to 600 kg/m^3; in the case of 19P/Borrelly they obtain a narrower range, 100-300 kg/m^3. However, an assumption has to be made regarding the tensile strength, e.g., considering it as a function of density or simply applying a constant value. By assuming zero strength, Davidsson (2001) analyzed a sample of 14 comets, and seven objects needed, to remain intact, densities in a range which coincides with the density range considered as likely for comets (Rickman 1989; Asphaug & Benz 1996).

Another method can be applied to comets which have an observable perihelion delay or advance, caused by the non-gravitational force due to nucleus sublimation and outgassing. If the non-gravitational force vector can be calculated with some accuracy as a function of orbital position, the mass of the nucleus can be estimated: then, if the size and shape of the nucleus are known with some accuracy, the density can be estimated.

Observations and subsequent modeling of break-up of cometary nuclei in addition to estimates of the mass and density can also give information about the internal nucleus structure. Cometary disruptions are an interesting opportunity to study unprocessed fragments of the nucleus. The structure and internal strength of the nucleus can be examined by investigations of the disruption process. The most prominent example was comet D/Shoemaker-Levy 9 (e.g., Noll, Weaver & Feldman 1996; Asphaug & Benz 1996) which was disrupted during a close encounter with Jupiter in 1992 and whose fragments finally collided with the planet in 1994. Another example of a comet for which such an analysis has been made is C/1999 S4 (LINEAR) (Weaver *et al.* (2001)). From observations made during the disruption of the comet and the runaway fragmentation that took place between 18 July 2000 and 23 July, Bockelée-Morvan *et al.* (2001) concluded that the relative abundances did not change during the breakup phase: at least in that case the nucleus had a homogeneous composition. Instead, from the observation of the fragmentation of comet C/2001 C2, performed with the SOHO Ultraviolet Coronagraph Spectrometer (UVCS), Bemporad, Poletto, Raymond *et al.* (2005) concluded that the collected evidence suggests that the material of the nucleus tended to break up very easily, and that at least two of the fragments had different composition.

An interesting opportunity to study structure and global composition of comets are sungrazing comets. A large number of them has been discovered by the Large Angle and Spectrometric Coronagraph (LASCO) on the SOlar and Heliospheric Observatory (SOHO) spacecraft. Many of the sungrazing comets observed so far are fragments of a single predecessor, the Kreutz comet (Marsden 1989). Most sungrazers are not observed past perihelion, including all the sungrazing comets detected by SOHO. If the reason is the complete evaporation of the nucleus, then the upper limit for its diameter is a few tens of meters for a nucleus consisting of pure water ice (Weissman 1983). Iseli *et al.* (2002) modeled sungrazing comets to constrain properties like radius, density, and tensile strength starting from the observation that these objects are completely destroyed. The application of the model to sungrazing comets showed that the maximum size of a comet which can be disrupted by sublimation alone is several tens of meters. This value depends on albedo, density, and perihelion distance of the comet, but is nearly independent on its thermal conductivity.

5. Hints from the origin of outer solar system planetesimals

Following Gladman (2005) one can say that our planetary system is embedded in a small-body disk of asteroids and comets, remnants of the original planetesimal population that formed the planets. Once formed, those planets dispersed most of the remaining small bodies: therefore, if we want to understand the internal composition of these bodies we have to understand the mechanisms that were responsible for the formation of this disk of objects.

During the last two decades, our understanding of the conditions under which planetesimals formed in the outer solar system has improved significantly. First of all we have to consider what could have been the composition of these bodies: this depends on the chemical evolution of the protosolar nebula at distances larger than 20 AU. The outer solar system is dominated by ices of different kind, being H_2O ice the most important. The kind of chemistry strongly depends on the reference model of the protosolar nebula. Our understanding of the chemical processes taking place in the primitive solar nebula has increased considerably as more detailed models of the dynamic evolution of such nebulae have become available. Early models (Grossman 1972) assumed that a mixture of hot gases present in the solar nebula cooled slowly maintaining thermodynamic equilibrium. At the beginning the more refractory vapors condensed, followed by the lower melting point materials. The model suggested that the major textural features and mineralogical composition of the Ca, Al-rich inclusions in the C3 chondrites were produced during condensation in the nebula characterized by slight departures from chemical equilibrium due to incomplete reaction of high temperature condensates. Fractionation of such a phase assemblage is sufficient to produce part of the lithophile element depletion of the ordinary chondrites relative to the cosmic abundances. This result is surprisingly good, given the very strong assumption of thermodynamic equilibrium made by the author. Morfill *et al.* (1985), instead, introduced the effect of localized turbulence that should be present when viscous accretion disks are considered. This information is used to develop a transport theory for dust and gas phases. In the paper the possible modifications by intermittent turbulence are discussed, chemical fractionation effects are analyzed, and the heterogeneity on small scales as well as the homogeneity on large scales of the primitive bodies in the solar system is examined within the framework of their theory. It is concluded that a turbulent protoplanetary nebula, if the turbulence is intermittent, may also provide the fastest means of growing planets from the solid dust component. The authors do not discuss about the structure of these aggregations, however it is clear that the suggested mechanism lead to very loose aggregates.

Also other authors, as Fegley & Prinn (1989), challenged the idea that the nebula was quiescent demonstrating that even major gas phase species such as N_2 and NH_3 could fail to achieve equilibrium due to the low temperatures and the concurrent slow chemical reaction rates in the region of the outer planets. At the low temperatures characteristic of the outer solar system, kinetics may mean that carbon remains as CO, since less oxygen is available to form water ice. Predicted rock/ice mass ratio in this case is 70/30, which gives a density of 2000 kg/m^3, similar to that observed for both Triton and Pluto. In the hotter nebula, carbon tends to be incorporated in CH_4 and the oxygen is then available to form water ice; rock/ice mass ratio in this case should be close to 1, giving a density of 1500 kg/m^3. Detection of CO is also consistent with low temperatures during the formation of bodies such as Triton, Pluto and other mainly icy bodies. However Fegley & Prinn (1989) point out that several processes can overlap modifying the original cometary chemistry, as a certain mixing of the protosolar nebula material with material formed in circumplanetary nebulae, as the Jovian and Saturnian ones, homogeneous and heterogeneous thermochemical and photochemical reactions, and disequilibration resulting from fluid transport, condensation, and cooling. Therefore, the interplay between chemical, physical, and dynamical processes should be taken into account if one wants to decipher the origin and evolution of the abundant chemically reactive volatiles (H, O, C, N, S) observed in comets.

This kind of considerations can be the basis to infer the possible composition of KBOs and of comets, in which we expect therefore to find a large amount of volatiles, carbon compounds such as CO being the dominant species, but a small amount of CH_4 of circumplanetary nebulae cannot be excluded. N_2 is also more probable than NH_3. The Halley data on the CO/CH_4 and N_2/NH_3 that are intermediate between those typical of the interstellar medium and those expected in a hotter nebula, seem to support this hypothesis. The original chemical evolution is only responsible for the initial chemistry of icy bodies, the further evolution could have partially altered it.

The process of agglomerate formation by gradual accretion of sub- millimeter solid grains has been studied both experimentally and numerically (e.g., Donn & Duva 1994; Blum *et al.* (2000)), and this investigation is in agreement with the idea that the primordial solar nebula was a suitable environment for the production of ice-rich grain clusters with a highly porous and fractal structure. These objects are accumulation of fluffy aggregates. If so, we have to expect that the present comets are remnants of this very primordial situation. The subsequent growth of these small clusters has been investigated by the use of sophisticated numerical modeling (Weidenschilling 1997), up to the point where 10 km sized planetesimals are formed. The size distribution of cometesimals growing by drag-induced collisions develops a narrow peak in the range tens to hundreds of meters. This occurs because drag-induced velocities decrease with size in this range, while gravitational focusing is negligible. Impact velocities have a minimum at the transition from drag-driven to gravitational accretion at approximately kilometer sizes. Bodies accreted in this manner should have low mechanical strength and macroscopic voids in addition to small-scale porosity. They will be composed of structural elements having a variety of scales, but with some tendency for preferential sizes in the range about 10100 m. In terms of internal structure, these bodies are very similar to the comet nucleus models proposed by Donn (1991) and Weissman (1986), known respectively as fractal and primordial rubble pile models. According to the fractal model, a comet is made of small cometesimals which are bound toghether by the gravitational force that, for these small aggregates, is pretty weak. Macro-porosity with large internal void spaces is therefore superimposed to the micro-porosity foreseen by the Donn (1991) model. The primordial rubble pile model is very similar to the fractal model, except that the cometesimals are more tightly packed, and welded together by collision-induced evaporation and the subsequent freezing of ice.

Recently laboratory simulation experiments were performed using micron-sized dust particles, impacting solid targets at various velocities. Again the result is consistent with the formation of open aggregates (Blum *et al.* (2000)). Slow bombardment of the target generally results in the formation of fluffy dust layers. At higher impact velocities, compact dust-layer growth is observed. Above a certain collision energy, the dust aggregates are disrupted. The Blum *et al.* (2000) experimental results suggest that aggregates restructuring in the solar nebula become an important process when the diameters of the dust agglomerates exceed a few centimeters. Dust aggregates below that size are not subjected to impact compaction. It has also been shown that heating and evaporation during a collision are rather limited even for collisions between large (~ 100 m) cometesimals, eventhough local thermal and possibly chemical alterations cannot be excluded (as in the primordial rubble pile model). Furthermore, bodies with sizes below a few tens of kilometers are not affected by gravitational compression. As a result, comets can be seen as low-density objects, formed slowly at low temperature, but characterized possibly by a complex internal structure which can allow their fragmentation under high-medium velocity impact conditions. Larger bodies, however, shall undergo different histories, due to the contribution of short (as ^{26}Al) and long-life radioactive decay, degassing and impact compaction.

6. Hints from thermal evolution modeling: Kuiper Belt objects

The thermal evolution modeling of Kuiper Belt objects has been dealt with two different kinds of models, corresponding to two different heritages and in turn to two different points of view: models originally developed for comet nuclei and models developed for icy satellites. One could say, following McKinnon (2002), that in one case we are scaling up from the traditional small cometary sizes, while in the other case we are starting from mid-sized icy satellites and moving downward to smaller sizes.

6.1. *Inheritage from comets modeling*

If we think to objects also larger than comets, like KBOs, as porous, ice-rich bodies, it is quite straightforward apply to them the models initially developed to study the thermal evolution of cometary nuclei. In fact it is very difficult to draw a clear line beyond which objects of a certain size begin to be compacted and differentiated: in fact, if for a (almost) homogeneous icy body we can follow the thermal and differentiation history, for a non-compact body characterized by heterogeneities and macro porosity it is more difficult. For this reason the approach commonly used for comets can be applied to a large variety of objects. This has been done by, for example, Capria, De Sanctis, Coradini *et al.* (2000), De Sanctis, Capria, Coradini *et al.* (2000), De Sanctis, Capria & Coradini (2001), Choi, Cohen, Merk *et al.* (2002), Choi, Brosch & Prialnik (2003), Merk, Breuer & Spohn (2002), Merk & Prialnik (2003). The underlying idea is that, if the link between comets and KBOs is real, then the comets observed properties can be used to constrain KBO models, including low formation temperature, low density (high porosity) and high volatile content; this means, in turn, that it is possible to study both kinds of bodies with the same theoretical models.

In order to study the thermal evolution and differentiation of porous, ice-rich bodies many models have been developed in the last years: a very complete discussion on the subject and many references can be found in the book by ISSI Comet Nucleus Team (2005); we will give here only few details.

In the currently used thermal evolution models, heat diffusion and gas diffusion equations are solved in a porous medium, in which sublimating gas can flow through the pores. A mixture of ices and dust is considered, and the flux from surface and subsurface regions is simulated for different gas and dust compositions and properties. The temperature on the surface is obtained by a balance between the solar energy reaching the surface, the energy re-emitted in the infrared, the heat conducted to the interior and the energy used to sublimate surface ices. When the temperature rises, ices can start to sublimate, beginning from the more volatile ones, and the initially homogeneous nucleus can differentiate giving rise to a layered structure in which the boundary between different layers is a sublimation front. Due to the larger, with respect to comet nuclei, sizes of

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Kuiper Belt bodies, and to the consequently higher content of refractories, the heating effect of radiogenic elements, both short and long-lived, is usually taken into account. So, these models consider two heating sources of comparable importance, one acting from the surface (solar input) and one present in the whole body: this can give origin to more complex thermal evolution patterns than in the case of comet nuclei.

To give an example, some results from a thermal evolution model that can be applied both to comets and to larger, denser bodies, developed by our group (Capria, De Sanctis, Coradini *et al.* (2000); De Sanctis, Capria, Coradini *et al.* (2000); De Sanctis, Capria & Coradini 2001) will be here briefly described.

The model is one-dimensional. The spherical nucleus is composed by ices (water, CO_2 and CO) and a refractory component. Water ice can be initially amorphous, and in this case more volatile gases can be trapped in the amorphous matrix and released during the transition to crystalline phase. The refractory material is described as spherical grains with given initial size distributions and physical properties. Energy and mass conservation is expressed by a system of coupled differential equations, solved for the whole nucleus:

$$\rho c \frac{\partial T}{\partial t} = \nabla[K \cdot \nabla T] + \sum_{i=1}^{n} Q_i + Q_{am-cr} + Q_{rad} \qquad (6.1)$$

$$\frac{1}{RT}\frac{\partial P_i}{\partial t} = \nabla[G_i \cdot \nabla P_i] + Q\prime_i \qquad i = 1, n$$

where T is the temperature, t the time, K the heat conduction coefficient, ρ the density of the solid matrix, c the specific heat of the material, Q_i is the energy exchanged by the solid matrix in the sublimation and recondensation of the i_{th} ice, Q_{am-cr} is the heat released during the transition from amorphous to crystalline form, Q_{rad} is the energy released by the decay of radioisotopes, R is the gas constant, P_i the partial pressure of component i, G_i its diffusion coefficient, and $Q\prime_i$ is the gas source term due to sublimation-recondensation processes.

For the radiogenic heating, the effects of ^{40}K, ^{232}Th, ^{235}U,^{238}U radioisotopes, and in some cases of ^{26}Al have been considered. The rate of radioactive energy release, Q_{rad}, is given by

$$Q_{rad} = \rho_{dust} \Sigma \lambda_j X_{oj} exp^{-\lambda_j t} H_j \qquad (6.2)$$

where ρ_{dust} is the bulk dust density, λ_j is the decay constant of the $j'th$ radioisotope, X_{oj} is its mass fraction within the dust, and H_j is the energy released per unit mass upon decay. The amount of radioisotopes in cometary nuclei is unknown and there is no way to measure it; we are assuming that the abundances of ^{40}K, ^{232}Th, ^{235}U,^{238}U are in the same proportion as in the C1 chondrites (Anders & Grevesse 1989).

This model has been applied to study the evolution of KBOs and Centaurs (Capria, De Sanctis, Coradini *et al.* (2000); De Sanctis, Capria, Coradini *et al.* (2000); De Sanctis, Capria & Coradini 2001). Here we will describe the results of this model applied to two different kinds of body, corresponding to two different hypotheses on the composition and internal structure of KBOs: a body whose composition and density are inherited from the typical ones of comet nuclei, and another one much more dense and rich in refractories.

6.2. *Dense and ice-rich Kuiper Belt objects*

We have applied the model to a typical Kuiper Belt body and have simulated its evolution under two different hypotheses, high and low density, in order to show possible differences

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in the evolution history. The two models were ran using as much as possible the same set of input parameters, and were followed on the same orbit for the same number of revolutions. The only difference in the two models is the initial density, to study the effect of this parameter in a typical thermal evolution.

Most of the model parameters assumed as reference are the values normally used for cometary nuclei composition. The body has a radius of 450 km, it is made by dust and ices of water and CO ($CO/H_2O = 0.01$) and the initial temperature is 20 K throughout the whole nucleus. The ice is initially amorphous. A value of 1000 kg/m^3 for the dust density simulates the fact that grains are the result of an accumulation process and are therefore highly porous. Pore radius has been fixed to 10^{-5} m. The orbit has a semimajor axis of 43 AU and an eccentricity value of 0.05. The only difference in the two models is the porosity, 0.8 for the "light" body and 0.3 for the "heavy" body. This gives origin to a density of nearly 400 kg/m^3 in the first case and of nearly 950 kg/m^3 in the second case. Both models were ran with and without the most important short-lived radioisotope, ^{26}Al, in the dust composition.

After several millions of years, depending on the amount and kind of radioisotopes in the models, the CO front reaches a quasi-stationary level in both models. The combined effect of radiogenic and solar heating -the latter coming from outside and the former uniformly distributed through the whole nucleus- leads to an increase of the overall temperature of the nucleus. The sublimation of CO ice has an important role in determining the abrupt slope change present in the thermal profile as soon as the quasi-stationary situation is reached. The thermal evolution of a higher and a lighter density body proceeds in a similar way, however the increase in the internal temperature is higher in the first case: in about 10^4 years the central temperature increases from 20 to 30 K due to the decay of ^{26}Al. When this radioisotope is absent, the increase of temperature is negligible for both kind of bodies, high and low density. The degassing of high density KBOs proceeds faster than for icy bodies. In the figure the internal temperature profile for a ^{26}Al rich (continuous line) and a ^{26}Al poor (dashed line) body are shown in the case of a high density composition: if the ^{26}Al is not contained in the bulk initial composition, the internal temperatures do not reach values sensibly higher than the initial ones. In the case of lower density composition, the figure (and the two curves) would be very similar, but much lower temperatures are reached, even with the presence of ^{26}Al.

It should be taken into account that, while the internal composition can be very different in the two hypotheses, these differences would be in any case hardly recognizable from the observation of the surface.

6.3. *Inheritage from satellite modeling*

Following McKinnon (2002), another analogous that can be used for the modeling of KBOs are the captured satellites such as Triton, the Pluto-Charon system and possibly Phoebe. In this case, the internal density assumed will be much higher than the one needed to explain the cometary activity, also according with recent measurements (9P/Tempel 1 guessed density should be very low, of the order of .5 g/cm^3).

The model by McKinnon (2002) is a spherically symmetric, conductive heat transport model with radiogenic heating and temperature dependent conductivities and heat capacities. Internal transport of volatiles is not considered; accretional heating is considered, along with radioactive heating. The composition is rock and ice, with a rock/rock+ice ratio of 0.7. The porosity is lower than in the traditional comet models, on the basis that it would be impossible for large KBOs have the typical comet porosities, due to the presence of hydrostatic pressure: rearrangement of the internal structure due to hydrostatic pressure is taken into account in the model. The body considered is at the threshold of

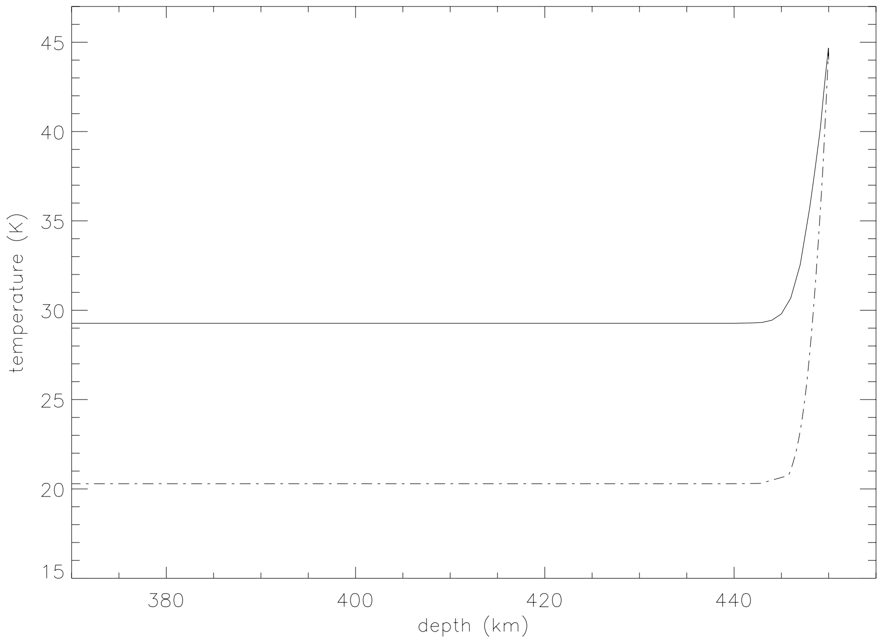

Figure 1. Internal temperature profile for a ^{26}Al rich (continuous line) and a ^{26}Al poor (dashed line) body with high density

pressure-induced densification. As far as regards the results, for a body with a radius of 100 km central temperatures reach 80 K in 50 Myr, then the body is slowly cooling. Irrespective of conductive models, bodies greater than 200 km in radius should have crystalline interiors: the critical size for large scale crystallization lies in the range 75-225 km. Larger KBOs have undergone chemical and structural evolution, whereas smaller ones could be considered cosmochemically primordial.

7. Hints from thermal evolution modeling: comets

The purpose of modeling comet nuclei is not to predict their behavior on the basis of an initial set of parameters, but to reproduce the observed behavior and thereby derive internal properties and processes characteristic of comet nuclei that are inaccessible to observations (see the book by ISSI Comet Nucleus Team (2005)). The general conclusion that emerges from simulations of the evolution of comet nuclei is that, essentially, a nucleus model of porous, grainy material, possibly made of gas-laden amorphous ice and dust, is capable of reproducing activity patterns of comets. From the results of these models, there are some general characteristics that may be expected of comets interiors: loss of the most volatile ices, stratified composition and inhomogeneous structure.

Calculations of the long-term evolution of comets far from the Sun, under the influence of radioactive heating, show that the internal temperatures attained may be quite high, at least several tens kelvin. As a result, comets may have lost volatiles that sublimate below about 40-50 K, that were initially included as ices, and, partially, less volatile species. Observation of such volatiles in comets suggests that they originate from amorphous H_2O ice undergoing crystallization or that radioactive heating was ineffective or did not occur. As far as regards the structure, while the inner part may have been altered by early

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evolution, the outer layers are altered by recent activity. Thus, the internal composition of comet nuclei is stratified, with increasingly volatile species at increasingly greater depths. Similarly, the internal structure of comets is very likely not uniform: density, porosity, H_2O ice phase and strength vary with depth. Increased porosity arises from volatile depletion, decreased porosity from recondensation.

Particularly in the case of comets, the dynamical history can have a strong influence on the resulting internal structure and composition of the body. Studying the evolution of short period comets, we always tried to simulate their dynamical history (Coradini, Capaccioni, Capria *et al.* (1997)) and we noticed that it has a strong effect. The dynamical evolution that brings a body from the Kuiper Belt region to the inner solar system is very complex (Stagg & Bailey 1989): this process (called multi-capture) involves the reduction of the revolution period, and this can be due to more than a close encounter with a giant planet in succession, beginning with Neptune and ending with Jupiter. The transfer from a Kuiper Belt orbit to a Jupiter family orbit lasts for a very long time, and can be reverted or stopped in any moment. This means that a body presently found on a short period orbit has a long dynamical history and was not injected directly from the Kuiper Belt. For this reason, a body displaced in the inner solar system will be already differentiated, at least in the layers close to the surface (De Sanctis, Capria & Coradini 2001). Differentiation processes due to volatile sublimation begin far from the inner part of the solar system; it is known that even a body on a Centaur-like orbit can be active (Womack & Stern 1999; Capria, Coradini, De Sanctis *et al.* (2000)).

8. The comet paradox

From all the above discussion, it is clear that when we analyze the bodies originated in the outer solar system we are facing a kind of paradox: we have from one side small, fragile, volatile-rich and low-density objects, and from the other side a population of much denser, larger and probably less ice-rich objects; we know that a dynamical link exists between them, but how can we explain this kind of dichotomy? There are, and there were from the beginning two kinds of population, or do they exist physical processes able to transform (or derive from) objects belonging to the Kuiper Belt in the typical comet nucleus? Nor the thermal evolution models nor the formation models can, to the moment, explain this paradox. Obviously there are several effects that depend strongly on the mass of the body, as can be seen by the analysis of planetary satellites, but it is difficult to understand to which extent the internal structure depends on the size and original density of the body. A process not yet discussed and that could shed some light on this dichotomy is the collisional evolution.

Let us imagine a large KBO still, at least partially, volatile-rich: could an impact produce, from this body, volatile rich fragments that could eventually become "real comet nuclei" as we know them? We need to make two assumptions: first, that large, differentiated objects exist (or existed) in the Kuiper Belt, and second, that an impact in this zone is able to shatter a body without completely destroying the volatile content of the fragments. As we saw in the preceding section the first assumption could not be a problem, and maybe impacts themselves contributed to this differentiation; the second assumption must be checked. As far as regards the impact rate, the dissipation time of the heat wave is of the order of millions of years, comparable with the impact rate computed by Farinella, Davis & Stern (2000). Can heat build up from impact to impact so as to trigger some global differentiation process? We already know that the collisions had an important role in shaping the Kuiper Belt, and that those collisions happened at quite a low relative velocity and were for this reason on average less disruptive than in the case of the asteroid main belt.

The role of the impacts in the thermal evolution of the bodies can be better understood using a heat conduction and gas diffusion model for comet nuclei of the kind described above (Orosei, Coradini, De Sanctis *et al.* (2001)): in particular, we could determine if the collisional non-disruptive history of KBOs is able to cause significant alterations in their volatile content. For certain combinations of model parameters, it has been found that the internal temperature of the body can easily reach a temperature of 180 K by the end of the accretion process; the outer layers of the body can be depleted in volatiles. Anyway, the outcome of the computations in the model is strongly dependent on uncertain physical parameters, such as thermal conductivity, radiogenic elements content and impact rate of accreting planetesimals, so it would be difficult to give a final answer on the basis of modeling.

9. A (possible) conclusion

We have seen that, while comet models explain quite well the observed properties of nuclei, KBO models can give very different outcomes depending on the assumptions made on ill constrained parameters such as ice fraction in the initial composition, porosity, density, thermal conductivity, radiogenic elements and dynamical evolution. The upper-size limit for which volatile-rich objects could have been differentiated is still unconstrained; measurements of the OPR (ortho para ratio) in water and other hydrogenated species is suggesting that comets have been preserved at low temperatures (Binzel *et al.* (2003)). If the link between comets and KBOs is real, the results of comets observation should be taken into account when constraining KBO models, in particular when dealing with low formation temperature, low density (high porosity) and high volatile content. Are two populations of KBOs (small, low-density and large, high-density objects) present from the beginning or are comets formed by fragmentation of large bodies only partially de-volatilized and characterized by porosity gradients? We need more data to clarify (or complicate) the problem.

How could we in a near future sample and measure the interiors of these bodies? In the case of masses and densities, it is in some sense simpler: we could use the dynamical properties of binaries systems, for example. To sample the interior properties is much more difficult. An interesting opportunity could be in situ measurements, from drilling to more destructive techniques, but they are probably not feasible in a near future.

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