The Structure of Kuiper Belt Bodies: Link with Comets

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The population of small bodies of the outer solar system is made up of objects of different kind and type, such as comets, Kuiper belt objects, and Centaurs, all sharing a common characteristic: They are rich in ices and other volatiles. The knowledge of the composition and properties of these bodies would help in 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 chapter we try to see what their thermal evolution could be, how it could bring about their internal differentiation, and how it could be affected by the orbital evolution. This is a way to link the surface properties, as probed by instruments, with the internal properties. We note that the comet activity is well interpreted if we assume that the comets are small, fragile, porous, volatile-rich, and low-density objects. This view, despite the strong differences noted in the few comet nuclei observed *in situ*, has not been disproven. On the other hand, the observations of the Kuiper belt objects indicate that it is possible that they are large, probably collisionally evolved objects (*Farinella and Davis,* 1996), perhaps with larger densities. We are now facing a kind of paradox: We have on the one hand the comets, and on the other a population of objects larger and possibly denser. We know that a dynamical link exists between them, but how can we go from one type of population to another? In this chapter the current status of our knowledge on the subject is reviewed, taking into account the results of thermal modeling and the results of observations.

1. INTRODUCTION

In the recent years a tremendous effort has been put forth to understand the origin and evolution of the Kuiper belt objects (KBOs). There are many unknown factors in attempting to identify the link between origin and evolution; however, there is one factor that is widely accepted as fact, namely that these objects are the source of short-period comets. This is not a minor constraint, since, at present, we have developed a noticeable amount of knowledge of comets, thanks to groundbased observations and to both current and past space missions.

Here we will try to identify the link between comets and bodies that are large enough to undergo a nonnegligible amount of differentiation. We will deal with the problem of the relation between KBOs and comets as seen from the point of view of thermal evolution models. What are the characteristics of comets deriving from their previous life in the outer part of the solar system? Is the gradual inward displacement of short-period comets able to totally obliterate their previous history? We are convinced that this is not the case, and we will try to demonstrate this through the reexamination of our previous results.

After the discovery of the first KBO, a large number of KBOs have been directly detected at different and increasing distances, thereby increasing the area of the solar system in which they are found. The orbits of the so-called classical Kuiper belt objects (see the chapter by Morbidelli et al.) fall into two main categories: objects with semimajor axis $a < 41$ 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 QB_1) that are not found in resonant orbits. Another component of the transneptunian region, the so-called scattered disk, has been added in the last few years: These objects are characterized by highly eccentric orbits extending up to ~130 AU and could be planetesimals that were scattered out of the Uranus-Neptune region into eccentric orbits. The Kuiper belt probably extends much farther than we presently know, and some objects could be found all the way to the Oort cloud.

Given the large extension of this region and the different thermodynamic conditions that can be present, it is impossible to exclude some variability in the structure of these bodies, both original (probably different volatile content) and due to different thermal histories (related in turn to the different composition and different sizes of the objects).

Overlapping with these local differences, the effect of impact evolution could have affected the different bodies, modifying their surfaces and contributing to their thermal evolution. Large impacts could have broken the large bodies apart, resulting in the origin of families of objects that are genetically related, but possibly different in composition, if the original body was already differentiated. Could this be the origin of some of the short-period comets? We are not certain, but our present knowledge seems to suggest this genetic relation. If so, the short-period comets could be an important source of knowledge about the KBOs. It cannot be excluded, however, that short-period comets are simply the tail of the original size distribution. The size distribution of KBOs is not well known, but it should be related to the primordial phases of solar system evolution, even if it has been changed by the resonances and the progressive depletion due to different phenomena. The size distribution of a population of objects can be considered a useful diagnostic tool for understanding the processes leading to the erosion and/or accretion of planetary bodies. From recent observations and theoretical studies, it is emerging that objects in the transneptunian region probably follow a complex size distribution (*Gladman et al.,* 2001). As far as the masses (and densities) are concerned, we have few data for the larger objects. Varuna, for which a density has been estimated (*Jewitt and Sheppard,* 2002) using the analysis of its lightcurve, could be a rotationally distorted rubble-pile object, so it would be porous at an unknown scale and low density (~1000 kg/m^3). Very recently, for the large KBO 2003 EL$_{61}$ a mean density of 2600–3340 kg/m^3 and a visual albedo greater than 0.6 have been estimated (*Rabinowitz et al.,* 2006). Using the new lightcurve data *Trilling and Bernstein* (2006) concluded that the bulk densities of KBOs and Centaurs likely lie in the range 500–1500 kg/m^3. This is roughly consistent with the average bulk density of short-period comets. This agreement, together with the dynamical considerations, may strengthen the proposed genetic link between KBOs and short-period comets.

On the contrary, surprisingly, *Jewitt and Luu* (2004) discovered that the Quaoar spectrum reveals 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, which is about 50 K. This discovery was followed by many other similar discoveries. This observation can be interpreted in different ways: as an indication of internal activity leading to the generation of ice volcanism, similar to that presently observed on Enceladus, or as the exposure of the underlying layers of crystalline ice, the upper layers of amorphous ice having been removed by impact.

Another possibility is that the ice on the surface has been heated above 110 K by meteorite impacts. In the first case, the crystallinity could be an indication of the differentiation that the object undergoes, probably due to the combined effects of radioactive decay, primordial bombardment, and compaction due to the body self-gravity. This will possibly be tested by laboratory measurement and accurate modeling.

Another example of the relevance of collision is the surprisingly high frequency of binaries (see chapter by Noll et al.). 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 et al.,* 2002; *Astakhov et al.,* 2005). 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 and Hyde,* 2005). This implies that the probability of collisions was higher than at present.

It is to be stressed again that KBO observations indicate a contradictory situation: On the one hand, the analysis of Varuna and other KBOs (*Jewitt and 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 porosity reduction and internal evolution. Density (porosity) is an observationally derived property having cosmogonical significance. We can also obtain hints on the internal structure 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 chapter we will try to combine the different sources of information and to see how they can be used to improve our theoretical approach and to reduce and limit the number of free parameters in the modeling of cometary activity. After the previous, very general definitions, we will briefly discuss the objects included in our review from the point of view of what 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; finally, we will try to reach some conclusions.

2. STRUCTURE AND COMPOSITION OF KUIPER BELT OBJECTS AS A RESULT OF THEIR ORIGIN

We will now describe the analogies with other objects and will discuss the link between these objects and the processes in the protosolar nebula that bring about KBO formation (the legacy of planetesimals) (see the chapter by Kenyon et al.). We focus our attention on processes that can bring about the formation of cold and fragile objects. The objects that we have to consider are KBOs, Centaurs, and short-period comets. In fact, even if their genetic relations are not perfectly understood, the work done over the years, mainly from a dynamical point of view, indicates that the objects in the Kuiper belt can be the source of both Centaurs and short-period comets (*Fernandez,* 1980; *Morbidelli,* 2004). In this framework Centaurs, with their instable orbits, represent bodies caught "on the way."

From a physical point of view all these bodies, having originated in the same place, should be closely related and should have the same intrinsic physical nature. There are obviously 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 volatile elements, which can under certain thermodynamic conditions lead to the development of an intrinsic activity due 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. Moreover, the high degree of "mobility" (*Morbidelli,* 2004) probably strongly influenced the subsequent history and hence the present structure and composition of many objects. 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.

Cosmogonical theories usually predict that the first condensates grow through different accumulation processes, which 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. Following *Gladman* (2005) one can say that our planetary system is embedded in a disk of asteroids and comets, remnants of the original planetesimal population. The outer solar system is dominated by ices of different kind, H_2O ice being 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. In 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 Grossman. *Morfill et al.* (1985), instead, introduced the concept that localized turbulence could be the most probable source of viscosity in accretion disks. Other authors, such as *Fegley and 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, and therefore less oxygen is available to form water ice. The 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 methane and the oxygen is then available to form water ice; the 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 icy bodies. However, *Fegley and 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; 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 type of considerations can be the basis for inferring the composition of KBOs and that of comets, in which we expect therefore to find a large amount of volatiles, with carbon compounds such as CO being the dominant species, but not excluding a small amount of CH_4 of circumplanetary nebulae. N_2 is also more probable than NH_3. The Halley data on CO/CH_4 and N_2/NH_3, which 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 submillimeter solid grains has been studied both experimentally and numerically (e.g., *Donn and 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 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 at which ~10-km-sized planetesimals are formed. If comets originated as icy planetesimals in the outer solar system, their nuclei have low strength, consistent with "rubble-pile" structure and inhomogeneities on scales of tens to hundreds of meters.

Weidenschilling (1997) presented results of numerical simulation of the growth of cometesimals, beginning with a uniform mixture of microscopic grains in the nebular gas. Coagulation and settling yield a thin, dense layer of small aggregates in the central plane of the nebula. The further evolution is dominated by collisions, and the relative collisional velocity is due mainly to the radial drift of the "cometesimals" interacting with the nebular gas. 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 ~10–100 m. Weidenschilling states that these properties are in good agreement with inferred properties of comets (*Donn,* 1991; *Weissman,* 1986; *Asphaug and Benz,* 1994), which may preserve a physical record of their accretion. However, the *Weidenschilling* (1997) scheme does not seem to be in agreement with the observation that the KBOs underwent a noticeable degree of collision (*Farinella and Davies,* 1996). Laboratory simulation experiments, performed using micrometer-sized dust particles impacting solid targets at various velocities, seem to indicate 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. It has also been shown that heating and evaporation during a collision are rather limited even for collisions between large (about 100 m) cometesimals, even though 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 possibly characterized by a complex internal structure that can allow their fragmentation under high- to medium-velocity impact conditions. We have verified that the presence of a limited amount of radioactive elements does not change their evolution. Larger bodies, however, if formed early in the evolution of the solar system, can undergo different histories, due to the contribution of short- (as ^{26}Al) and long-life radioactive decay, degassing, and impact compaction.

Detailed modeling of accretion in a massive primordial Kuiper belt was performed by *Stern* (1996), *Stern and Colwell* (1997a,b), and *Kenyon and Luu* (1998, 1999a,b). While each model includes different aspects of the relevant physics of accretion, fragmentation, and velocity evolution, the basic results are in approximate agreement. In general, all models naturally produce a few objects the size of Pluto and approximately the right number of 100-km objects, on a timescale ranging from 10^7 to 10^8 yr. The models suggest that the majority of mass in the disk was found in bodies approximately 10 km and smaller. An upper limit for accretion timescales in the Kuiper belt region seems to be the formation time of Neptune, since it is assumed that the formation of Neptune efficiently terminated the growth in the Kuiper belt region (*Farinella et al.,* 2000), inducing eccentricities and inclinations in the population high enough to move the collisional evolution from the accretional to the erosive regime (*Stern,* 1996). The formation timescale is crucially important in determining the thermal evolution of a body. The strong heliocentric distance dependence of the growth time is consistent with a large radial gradient in their hydration properties across rather modest radial distance differences (*Grimm and McSween,* 1993). Detailed models of KBO accretion show that these objects can form on a timescale of 10–100 m.y., provided very-low-velocity dispersions are maintained (*Kenyon,* 2002). In this case the effect of radioactive elements can be negligible. For this reason, in what follows we have treated the thermal evolution in the presence or the absence of short-lived radioactive elements.

3. THE EFFECT OF RADIOACTIVE ELEMENTS AND POROSITY

We have described the possible composition of KBOs on the basis of their origin. In this section, we consider the effect of two parameters that can strongly condition the evolution of KBOs, beginning with the effects of radioactive element decay. First, we have to take into account the timescale of evolution. In fact, if the formation time is on the order of 10–100 m.y., the KBOs are probably heated by trapped ^{26}Al or other short-lived nuclei only at the beginning of their lives. Short-lived radionuclides are characterized by half-lives that are significantly shorter (i.e., $\leq$~100 m.y.) than the 4.56-Ga age of the solar system. Based on recent data, there is definitive evidence for the presence of two new short-lived radionuclides (^{10}Be and ^{36}Cl) and a compelling case can be made for revising the estimates of the initial solar system abundances of several others (e.g., ^{26}Al, ^{60}Fe, and ^{182}Hf). The presence of ^{10}Be, which is produced only by spallation reactions, is either the result of irradiation within the solar nebula (a process that possibly also resulted in the production of some of the other short-lived radionuclides) or of trapping of galactic cosmic rays in the protosolar molecular cloud. On the other hand, the most accurate estimates for the initial solar system abundance of ^{60}Fe, which is produced only by stellar nucleosynthesis, indicate that this short-lived radionuclide (and possibly significant proportions of others with mean lives $\leq$10 m.y.) was injected into the solar nebula from a nearby stellar source. As such, at least two distinct sources (e.g., irradiation and stellar nucleosynthesis) are required to account for the abundances of the short-lived radionuclides estimated to be present in the early solar system.

The levels at which the short-lived radionuclides ^{26}Al, ^{41}Ca, and ^{60}Fe (and probably ^{36}Cl) are maintained in the galaxy are significantly lower than those inferred from meteorites in the primordial solar nebula, and after a delay of ~10^8 yr essentially none of these radionuclides remains in the molecular cloud from which the solar system formed (*Harper,* 1996; *Wasserburg et al.,* 1996; *Meyer and Clayton,* 2000). As such, some nearby processes were creating radionuclides within ~10^6 yr of the birth of the solar system. It is clear that more than one process was involved, since there is no proposed source that can simultaneously produce enough ^{10}Be and ^{60}Fe. The most plausible source of ^{60}Fe in the early solar system is a Type II supernova. When that supernova injected ^{60}Fe into the material that formed the solar system, it is also likely to have injected other short-lived radionuclides such as ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{53}Mn (*Meyer and Clayton,* 2000; *Goswami and Vanhala,* 2000; *Meyer,* 2005). Therefore, while the inferred initial abundance of ^{60}Fe in the early solar system places its formation near a massive star that became a supernova, the timing of this event and the distance from this supernova are uncertain. However, heating by ^{26}Al may well take place during the accretion process itself; moreover, the accretion rate is not linear in time. Thus, the core of an accreting body may be significantly heated before the body reaches its final size long after the decay of ^{26}Al.

The effect of combined growth and internal heating by ^{26}Al decay was investigated by *Merk and Prialnik* (2003) for an amorphous ice and dust composition, without other volatiles. They found that small objects remain almost unaffected by radioactive heating while the effect on larger bodies is not linear with size. There is an intermediate size range (around 25 km), where the melt fraction and duration of liquid water are maximal, and this range depends strongly on formation distance (ambient temperature). This internal evolution should bring about a kind of recompaction of these objects. In fact, if liquid water ice is present, the density of the layer containing it is certain to be higher than the density of ice.

The studies of KBO lightcurve data (*Trilling and Bernstein,* 2006) indicate that the bulk densities of KBOs and Centaurs likely lie in the range 500–1500 kg/m^3. The study by *Consolmagno et al.* (2006) of KBO spins suggests that the mean density of these objects is approximately 450 kg/m^3. These estimates are roughly consistent with the average bulk density for short-period comets. This agreement may strengthen the proposed genetic link between KBOs and short-period comets. The KBOs would likely have bulk compositions similar to comets and thus similar nominal grain densities. As a result, KBO bulk porosities are likely to be in the 60–70% range. However, this analysis seems to be limited to the "medium-sized" KBOs. The largest KBOs are substantially denser. Pluto has a bulk density of 2.0×10^3 kg/m^3. The Pluto-sized 2003 EL$_{61}$ is a rapid rotator (with a period of 3.9 h) and may have a bulk density in the range of $2.6–3.3 \times 10^3$ kg/m^3 (*Rabinowitz et al.,* 2006). These objects, like the largest asteroids, are probably coherent with low macroporosity.

Continuing work on comets has produced some indication of their bulk density. Analysis of ejecta trajectories observed during the Deep Impact encounter with Comet 9P/Tempel 1 indicates a low bulk density (*A'Hearn et al.,* 2005). *Davidsson and Gutierrez* (2004, 2006) estimated densities for Comets 19P/Borrelly and 81P/Wild 2 by analyzing nongravitational orbital changes. Wild 2 density is estimated between 380 and 600 kg/m^3 and 19P/Borrelly between 180 and 300 kg/m^3. Comet rotation period data also support a strengthless rubble-pile model with average low bulk densities. While all these estimates are model-dependent and have large error bars, it appears safe to say that comets have very low bulk densities. To put these numbers in perspective, we need to look at comet composition and the grain density (porosity-free density) of those materials. To first order, comets are mixtures of water ice with a dust composed of hydrated silicates, mafic silicates, and organics. While there are a number of other volatile species, water ice dominates the mass balance of the volatiles. Water ice has a grain density of 930 kg/m^3. Cometary dust compositions are not yet well known, but a reasonable analog may be CI carbonaceous chondrites, which are composed of the same sort of silicate and organic mixture thought to dominate the cometary dust. CI carbonaceous chondrites have a grain density of 2.27×10^3 kg/m^3. Dust to ice ratios are thought to be on the order of 2 to 1, which would make the theoretical grain density of a comet approximately 1.8×10^3 kg/m^3. It is unlikely that cometary materials will have grain densities much lower than this number. Methane and nitrogen ices have densities in the $0.8–0.9 \times 10^3$ kg/m^3 range, not much lower than water ice, and their low mass balance would not strongly affect the overall bulk composition of the comet. The dust is unlikely to be much less dense since the hydrated silicates have grain densities in the $2.2–3.0 \times 10^3$ kg/m^3 range and mafic silicates are much denser. If the "grain density" of a cometary mix of materials is 1.8×10^3 kg/m^3 and comet bulk densities range around 0.5×10^3 kg/m^3, the implication is that comets have very large porosities. For Tempel 1, a 0.62×10^3 kg/m^3 bulk density would translate into a bulk porosity of 60%. For a nominal cometary bulk density of 0.5×10^3 kg/m^3 the bulk porosity would be approximately 65%. This level of porosity indicates that cometary structures are, not surprisingly, essentially fluffy balls with more empty space than solid material. Therefore it could be reasonable to assume that small and intermediate KBOs are completely, or at least in large part, porous (*Capria and Coradini,* 2006).

If we assume that short-period comets are the smallest members of the KBO family, in order to use their properties as an example of KBOs, we have also to take into account the effect of the slow migration of short-period comets in the inner solar system. Comets lose their volatiles differentially, and unfortunately the abundance ratio of ejected volatiles in the coma does not represent the nucleus abundances (*Huebner and Benkhoff,* 1999). It should be mentioned that nucleus models succeeded in explaining the release of gases along cometary orbit only when the effect of gas diffusion taking place in a porous medium was simulated (*Huebner et al.,* 2006).

The recent findings of the Deep Impact mission strongly reinforce the arguments cited above. The Deep Impact instruments revealed that, even if the surface of Tempel 1 is remarkably homogeneous in albedo and color, three discrete areas have the spectral signature of water ice. These regions cover a small fraction of the surface, only 0.5% (*A'Hearn et al.,* 2005; *Sunshine et al.,* 2006). Moreover, it is significant that the extent of this ice on the surface of Tempel 1 is not sufficient to produce the observed abundance of water flux observed in the comet's coma, meaning that there are sources of water from beneath the comet's surface. This is an important discovery that confirms the porosity of the surface layers. The comet surface of 9P/Tempel 1 seems to be covered by fine particles because the impact excavated a large volume of very fine (microscopic) grains, probably preexisting either as very fine particles or as weak aggregates of such particles. This fine material layer must be tens of meters deep (*A'Hearn et al.,* 2005). Studying the ejecta at very late stages, the overall strength of the excavated material was determined to be <65 Pa, and the bulk density of the nucleus is estimated at roughly 0.6×10^3 kg/m^3. This low density implies a porous structure of the comet nucleus. The porosity of dust mantle and comet layers has been assumed in some thermal evolution models of comet nuclei (*Capria et al.,* 2001, 2002; *De Sanctis et al.,* 1999, 2003, 2005, 2007; *Prialnik et al.,* 2004; *Huebner,* 2003; *Huebner et al.,* 2006).

4. THERMAL MODELS OF KUIPER BELT OBJECTS

Given the previous considerations, we are now able to describe the kind of modeling that we can develop. We assume therefore that KBOs are volatile-rich, porous objects, as a result of the limited observational data on KBOs and the indications from comets to which KBOs are genetically related. The thermal evolution models of KBOs were treated with two kinds of approaches, corresponding to two different points of view, both legitimate given the great uncertainty that exists about the internal structure of KBOs: models originally developed for comet nuclei and models originally developed for icy satellites (see chapter by McKinnon et al.). 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.

If we also think that objects larger than comets, such as KBOs, can be porous and ice-rich bodies, it is straightforward to 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 between compact and differentiated objects of a certain size and noncompact, porous, almost homogeneous icy bodies. The approach commonly used for comets can be applied to a large variety of objects. This has been done by, for example, *Capria et al.* (2000), *De Sanctis et al.,* (2000, 2001), and *Choi et al.* (2002), who used models derived from comet nuclei models to study Centaurs and KBOs. The underlying idea is that, if the link between comets and KBOs is real, then the observed properties of the comets 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 over the last few years; a complete discussion on the subject and an exhaustive reference list can be found in the book by the ISSI Comet Nucleus Team (*Huebner et al.,* 2006). We will give here only a 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 reemitted 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 sizes of KBOs with respect to comet nuclei, 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 entire body; this can give rise 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 KBO bodies, developed by our group (*Capria et al.,* 2000*; De Sanctis et al.,* 2000, 2001), will be briefly described here.

The nucleus is assumed to be spherical and composed of 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 assumed to be in grains, spherical in shape. The initial grain size distribution can be given as well as the grain physical properties. Energy and mass conservations are expressed by a system of coupled differential equations, solved for the whole nucleus. The heat equation is

$$\rho c \frac{\partial T}{\partial t} = \nabla(K\nabla T) + \sum_i Q_i + Q_{tr} + Q_{rad}$$

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 the energy exchanged by the solid matrix in the sublimation and recondensation of the ith ice, Q_{tr} the heat released during the transition from amorphous to crystalline form, and Q_{rad} the energy released by the decay of radioisotopes. The gas equation is

$$\frac{\partial \rho}{\partial t} = -\nabla \Phi_i + Q_i'$$

where Φ_i is the gas flux and Q_i' is the source term that is coupled with the heat equation. For radiogenic heating, the effects of ^{40}K, ^{232}Th, ^{235}U, and ^{238}U radioisotopes, and in some cases ^{26}Al. have been considered. The rate of radioactive energy release, Q_{rad}, is given by

$$Q_{rad} = \rho_{dust} \sum \lambda_j X_{0j} H_j e^{-\lambda_j t}$$

where ρ_{dust} is the bulk dust density, λ_j is the decay constant of the jth radioisotope, X_{0j} is its mass fraction within the dust, and H_j is the energy released per unit mass upon decay.

The amount of radioisotopes is unknown and there is no way to measure it; in these models it has been assumed that the abundances of long-lived radioisotopes are in the same proportion as in the C1 chondrites (*Anders and Grevesse,* 1989), while the amount of ^{26}Al is variable in the different cases studied. Here we will describe the results of this model applied to two different kinds of bodies, corresponding to two different hypotheses about 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.

4.1. Low-Density Ice-rich Kuiper Belt Objects

In this case we consider the thermal evolution of KBOs with the assumption that they are similar to cometary nuclei, so we are using parameters that are considered as standard in cometary models. When we say standard parameters, we refer to a range of values that are considered typical for comets, derived by observations, laboratory experiments, and *in situ* measurements. Because it is impossible to change and test all the parameters, we have analyzed which parameters are critical for these models and have built our cases around them.

We have seen that there is a limited number of key parameters: the amount and type of radioisotopes, the body composition (especially the amount of dust), the size, and the thermal conductivity. These factors affect the evolution in different ways. The amount and kind of radioisotopes provide different heating rates that are also a function of time. The ^{26}Al radioisotope is a very intense heat source, and its abundance strongly affects the evolution of the body. The presence of ^{26}Al in KBOs is debated: Due to the short half-life of this radioisotope (10^5 yr), the formation should have to take place within a few million years. The total amount of radioisotopes is a function of the amount of the refractory materials (dust) in the nucleus. At the same time, the dust affects the overall thermal conductivity: The larger the dust/ice ratio, the larger the thermal conductivity. The combination of these two parameters strongly increases the overall process of heat transfer.

The structure of water ice also influences the thermal evolution of the body. Amorphous ice can be a very inefficient heat conductor. The crystallization process is a strong internal heat source that under particular conditions (very low conductivity) gives a runaway increase of internal temperature. The structure of the body in terms of porosity and pore radius has a strong influence on the thermal conductivity and, consequently, on the internal temperature; porous media are inefficient conductors. Low conductivity results in higher temperature.

The size of the body is important. Earlier work has shown that radiogenic heating is not efficient for small bodies. The values adopted in these models to describe the cometary nuclei composition have been largely discussed in several reviews (*Festou et al.,* 1993; *Rickman,* 1998) and also by the ISSI Comet Nucleus Working Group (*Huebner et al.,* 2006), and they are broadly accepted. For these models (*De Sanctis et al.,* 2001) we have assumed an initial temperature of 30 K throughout the whole body, which is a plausible solar nebula temperature in cometary formation regions (*Yamamoto,* 1985; *Yamamoto and Kozasa,* 1988). A value of 1000 kg m^{-3} for the dust density takes into account the fact that grains are the result of an accumulation process and are therefore highly porous. The emissivity value is 1, the initial porosity is 0.8, and the initial pore radius has a value of 10^{-5} m. In these models we are assuming a fairly low initial amount of CO, but we are considering only the fraction of CO existing as its own ice.

The combined effect of radioisotopes and solar heating, the latter coming from outside and the former uniformly distributed through the whole body, leads to an increase in the overall temperature of the nucleus. The internal temperature gradually increases but never reaches a value high enough to permit the crystalline phase transition: The amorphous ice is preserved. It must be recalled that the central temperature strongly depends on the thermal diffusivity.

The main results of the thermal evolution models applied to "comet-like" classical KBOs is that the internal heating due to radio-decay can be sufficient to mobilize volatiles, giving rise to a compositionally layered structure. In the upper 100 m below the surface, the most volatile ices (such as CO) are completely absent due to the combined effects of solar and internal heating. Due to radiogenic heating, the internal temperature may become high enough to permit the sublimation of CO (or similar hypervolatile ices) from the inner layers. The gas is free to circulate in the body pore system and can recondense in those layers at lower temperature. The nucleus that results from the radiogenic heating has a layered structure made of interlaced layers of frozen CO and layers depleted (with respect to the initial amount) of CO ice. This layered structure with "CO-enriched" and "CO-depleted" zones is due to the fact that the central temperature tends to rise above that of the sublimation temperature of CO.

If the amount of the short-lived radioisotopes, such as ^{26}Al, is low or negligible, the models foresee that the CO ice is confined in the nucleus interior. The depth at which the volatiles are confined depends on the type of radioactive elements and on their quantity. Obviously, small amounts of radioactive elements have little influence on the thermal evolution of KBOs.

From these simulations (*De Sanctis et al.,* 2001) (see Fig. 1) it can be seen that if the body is ice-rich and of low density an undifferentiated core can survive, depending mainly on the type and amount of radiogenic elements contained in the body, but also on the physical parameters assumed, such as thermal conductivity, porosity, radius, etc. The bodies emerging from this scenario retain amorphous ice because the central temperature does not rise too much. It must be recalled that the overall thermal conductivity computed for our models is quite large, and this is a key parameter for the increase of the internal temperature. Much smaller conductivities can give different results with a runaway temperature increase.

In these models we do not consider the presence of trapped volatile molecules. Laboratory experiments on sublimation of mixtures of amorphous water ice and volatiles suggest that a substantial fraction of these volatiles can sublimate when the phase transition occurs. From our results the volatiles, bound within the amorphous ice, are preserved and are present through the whole nucleus until the body is in the Kuiper belt. In these cases, one source of volatile molecules, such as CO, observed in comet comae, could be the trapped volatiles liberated when the phase transition of the amorphous ice occurs.

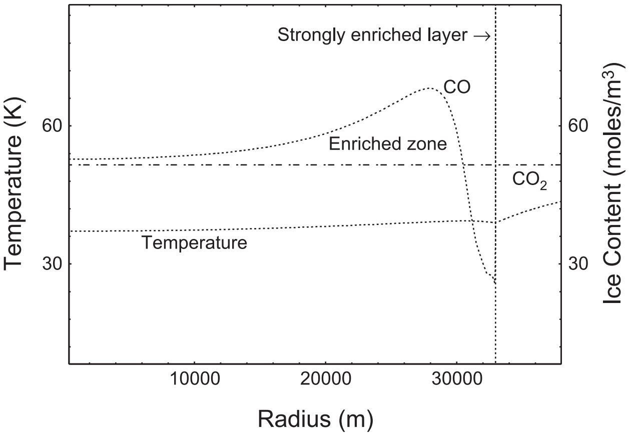

Fig. 1. Thermal profile, CO_2, and CO profiles of a typical KBO model. The scale on the left refers to the temperature; the scale on the right refers to the volatile ice content in the body. It can be seen that the amount of CO_2 is constant and unchanged throughout the entire nucleus, while the CO amount shows enrichment and depletion at different depths (from *De Sanctis et al.,* 2001).

These results are strongly dependent on the amount and kind of radioisotopes assumed. In fact, assuming a larger quantity of ^{26}Al, *Choi et al.* (2002) found that, depending on the initial parameters, the interior may reach quite high temperatures, losing the ices of very volatile species during early evolution. Their models indicate that, in some cases, the amorphous ice crystallizes in the interior, and hence some objects may also lose part of the volatiles trapped in amorphous ice.

According to their models, KBOs may have lost entirely all volatiles that sublimate below ~40–50 K, which were initially included as ices, and may have partially lost less-volatile ices as well. However, in this case the conclusion is valid only on the assumption that the entire surface area is, on average, equally heated. As a result, the internal structure of KBOs is most probably not uniform; rather, density, porosity, H_2O ice phase, and strength all vary with depth.

All the developed models of KBOs indicate that the internal temperature profile may have been substantially affected by both short- and long-lived radionuclides, with accompanying changes in composition and structure (see Figs. 2a,b). Moreover, the models indicate that regions enriched in volatile species, as compared with the initial abundances assumed, arise due to gas migration and refreezing.

These changes in structure and composition should have significant consequences for the short-period comets, which are believed to be descendants of Kuiper belt objects. The evolution of such a body when injected in the inner solar system will be characterized by outbursts of volatiles, when the volatile-enriched layers reach the sublimation temperature. However, the evolution of the temperature profile and the structural modifications are a function of the accretion times of KBOs (the amount of radioactive elements), dust-to-ice mass fraction, density, etc. Nevertheless, we may state that if KBOs did experience radioactive heating, their structure and composition were altered mainly to the extent of considerable loss of volatiles and significant departure from internal homogeneity.

4.2. More-Dense Dust-rich Kuiper Belt Objects

We have applied the model to a Kuiper belt body with larger density with respect to the previous one, in order to show possible differences in the evolution history. In this case, most of the model parameters assumed as reference are the values commonly used for cometary nuclei composition (*Huebner et al.,* 2006). The body has a relatively small radius (100 km), is made up of dust and ices of water and CO_2, and the initial temperature is 20 K through-

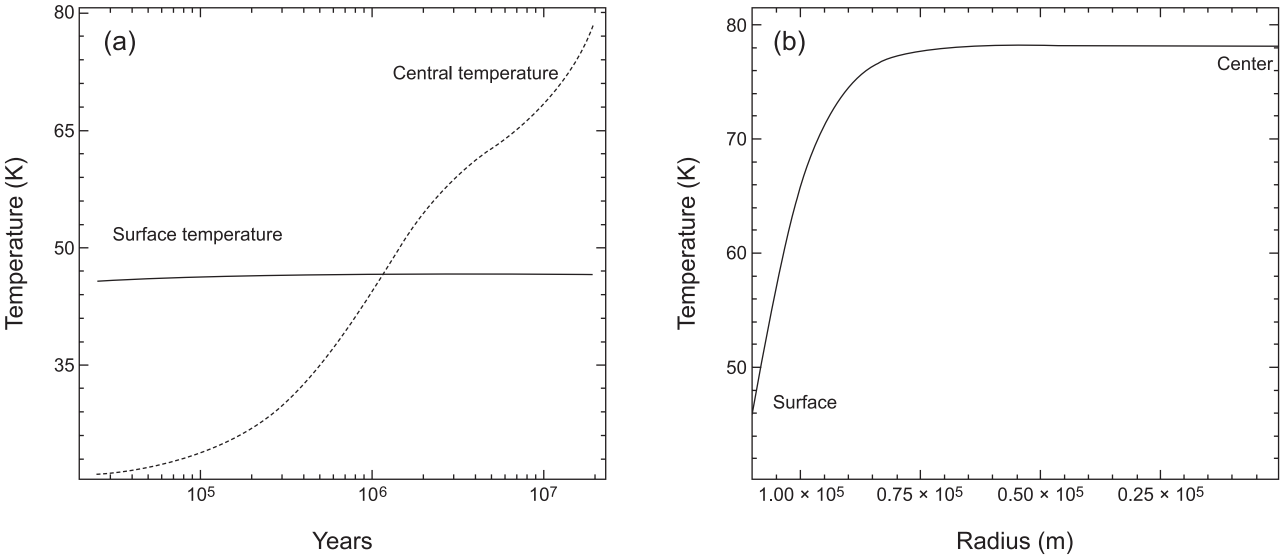

Fig. 2. **(a)** Evolution of the surface and central temperature for an icy-dense KBO. In this case, we have followed the evolution of the body for 10^7 yr, a timescale in which the effect of the short-lived elements becomes apparent. In fact, while the surface temperature remains almost constant, the central temperature increases up to 80 K. **(b)** Thermal profile of the same body shown in **(a)**. In this case the thermal profile is opposite of that shown in Fig. 1. Here the maximum temperature is in the center, and the maximum gradient, after 20 m.y., is close to the surface, which remains almost isothermal due to the limited amount of heat received from the Sun. Volatiles lost from the central part are quenched again when moving outward, where they meet very cold layers.

out the entire nucleus. The ice is initially amorphous. The overall density of the body is 1600 kg/m^3 and has a porosity of 0.3. The orbit has a semimajor axis of 43 AU and an eccentricity value of 0.05. In this model a small amount of the short-lived radioisotope, ^{26}Al, is included in the dust composition. The combined effect of radiogenic and solar heating — the latter coming from outside and the former uniformly distributed throughout the entire nucleus — leads to an increase in the overall temperature of the nucleus. The central temperature increases, reaching the sublimation temperature of the most-volatile ices. The amorphous-crystalline transition can be activated at such a temperature at a very low rate, possibly releasing the trapped gas. However, the internal temperature is not high enough to have liquid water. We can speculate that bodies like this can be deeply altered due to the radiogenic heating losing the hypervolatile ice, as CO (see Fig. 3).

Moreover, in order to verify the long-term behavior of an object poor in high-volatility elements and less porous than typical comets, we have also considered a class of models in which the conditions are closely similar to those of satellites. Table 1 reports the different models that we have developed. These models differ in dust/ice ratio, density, and content of radioactive elements. A model without ^{26}Al was run in order to have a reference case. The results of these models are also reported in Fig. 3, in which the different curves are labeled with the same names as those used in Table 1.

As should be expected, bodies having higher dust content are also characterized by a higher thermal conductivity. The heat generated inside the body is transported toward the surface, and a large part of the body is characterized by a noticeable increase in temperature. In the body in which the dust/ice ratio is higher, the central temperature increases, in about 10^5 yr, from 20 to 230 K because of the decay of ^{26}Al.

We have therefore verified if our results are compatible with solid convection. This has been done by assuming that the convection can take place if the critical Rayleigh number has been overcome. We have used two different definitions

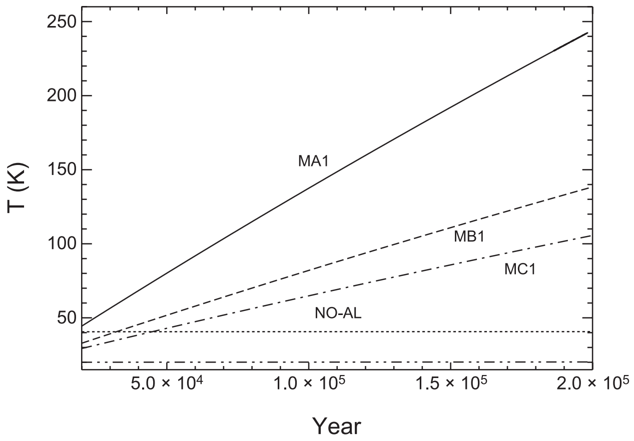

Fig. 3. Central temperature evolution for the low-volatile KBO models described in Table 1. Here we see that when the amount of dust increases, if short-lived elements are present, the central temperature increases up to values that allow the crystallization of water ice.

TABLE 1. Low-volatile KBO models.

Models	MA	MB	MC	NO-AL
Composition	Dust + H_2O	Dust + H_2O	Dust + H_2O	Dust + H_2O
Dust/Ice	5	2	1	5
ρ bulk (g cm^{-3})	1583	871	287	1583
Al_{26}	Yes	Yes	Yes	No
T_0 (K)	20	20	20	20
Radius (km)	200	200	200	200
a	50	50	50	50
e	0.03	0.03	0.03	0.03
Albedo	0.06	0.06	0.06	0.06
Porosity	0.3	0.45	0.7	0.3

of the number: in the presence (R_{a1}) or in the absence (R_{a2}) of radioactive elements. We can assume

$$R_{a1} = \frac{\alpha\rho g \Delta T_{max} \Delta r^3}{k_d \eta}$$

$$R_{a2} = \frac{\alpha\rho g H \Delta r^5}{K \eta k_d}$$

$$\eta = \eta_0 \exp\left[A\left({}^{T_m}\!/_{T} - 1\right)\right]$$

$$g = \frac{4}{3}\pi G R$$

where ρ is the bulk density, α the coefficient of thermal expansion, k_d the thermal diffusivity, K the thermal conductivity, η the solid viscosity, g the gravitational acceleration, H the heat generation due to the presence of radioactive elements, ΔT the thermal gradient in the layer considered as Δr, T_m the melting temperature, A a dimensionless coefficient, and $(Ra)_{Crit}$ the critical Rayleigh number, which following *Schubert et al.* (2001) could be assumed to be between 1000 and 2000.

R_{a1} and R_{a2} are respectively the definition of the Rayleigh number in the absence or in the presence of radioactive elements. We have also assumed that convection can take place if $Ra > (Ra)_{Crit}$, following *Schubert et al.* (2001): This approach is the so-called parametric convection. The most difficult parameter to evaluate is the layer thickness, Δr. In our case we have considered a layer that is compatible with the discretization of the process that we have assumed. Since we have a grid, divided in steps of finite dimensions, we have verified in which step the condition of convective instability is satisfied. Then we have considered two steps around the value where the vertical gradient is maximum, and it corresponds to ~10 km. We have verified that, assuming $H = 4.3 \times 10^{-3}$, $(Ra)_{Crit} \approx 1000$ only when radioactive elements are present and $\eta_0 = 1014$ Pa, then $R_{a2} \sim 1500$–3000 and convection is possible.

We can therefore state that, when a small amount of radioactive elements is present, the combined effect of solar radiation and radiogenic heating leads to KBOs that are strongly volatile depleted, at least in their upper layers. The KBOs are also highly differentiated: A typical result is that interlaced layers that are CO-depleted and CO-enriched are found, particularly when very cold, porous icy bodies are considered. If this result is confirmed, the evolution of KBOs injected in hotter parts of the solar system will be characterized by an outburst of volatiles when the enriched layers reach sublimation temperature. Finally, an undifferentiated core can survive, depending on the size and radiogenic-element content of the body.

When KBOs are characterized by a high content of ^{26}Al, chondritic value, we have a strong heating of the internal layers, surmounted by a layer still remaining at lower temperature; only these layers can be still enriched in volatiles. The two classes of models behave in a completely different way. In this second case, the amount of volatiles is much lower and can be further affected by the dynamical evolution: The layer very close to the surface can be further depleted when the body is injected in the inner part of the solar system, so only a shell of volatile-rich ice could be present. Again, we form interlaced layers of different composition and characteristics, but in the first case high-temperature, volatile-rich ice is dominant, while in the second case the shell of volatile-rich ice is limited. These bodies can be also characterized by the onset of convection.

In both cases, collision in differentiated bodies can lead to fragments of different volatile content and different structural characteristics. Comets can be generated by the fragmentation of a volatile-rich body, or by the destruction of a largely differentiated object, still preserving in its interior a certain amount of volatile-rich ice.

5. THE JOURNEY IN THE INNER SOLAR SYSTEM: THE KUIPER BELT OBJECT–COMET LEGACY

In conclusion, the results obtained up to now are promising, although some uncertainties are still present. The amount of short-lived radioactive elements is not easy to determine, as it is strongly related to the formation timescale. The shorter the time of formation, the higher the amount of radioactive elements can be. Different initial conditions can result in completely different situations; however, thermal processes related to the solar radiation, occurring close to the surface, and heating processes related to the radioactive element decay affecting the deeper layers can bring to complex internal structures. If the amount of short-lived radioactive elements is chondritic, then the global amount of volatiles is depleted, and without them the cometary activity cannot be explained. However, the more-depleted objects still preserve some gas in the intermediate layers, as shown by our models. In a previous paper (*Capria and Coradini,* 2006), we have left this problem open. Here, after a series of efforts to model comets and KBOs, we reach the conclusion that the tremendous variability observed in comets can either be pristine or can be related to the collisional disruption of previously differentiated large objects, which can give rise to bodies with different volatile content. Overlapping these differences are the effects of the collisional and thermal evolution of these bodies, which again can strongly alter the overall structure or volatile content. In any case, in order to explain consistently the present behavior of comets, two main characteristics shall be preserved: porosity and the presence of high-volatility gases. Moreover, great variability in the object can be the result of further dynamical evolution.

We know that there exist bodies located on unstable orbits that are surely linked to KBOs; these are referred to as Centaurs. A growing number of these bodies 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 and Duncan,* 1994; *Hahn and 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 formerly resided in the Kuiper belt and only recently have they been delivered into their current orbits. The different behavior of Centaurs has been tentatively attributed not only to different compositions and volatile contents, but also to the presence or absence of a crust (primordial irradiation mantle?) on their surface. Such a crust could inhibit activity and, in the case of organic compounds, redden the spectra.

This common origin with KBOs makes the Centaurs very interesting, because they could provide compositional information on the more distant Kuiper belt objects and could also provide information about their subsequent processing. If Centaurs are bodies that are coming from the Kuiper belt and are waiting to become short-period comets, we can use them to infer the characteristics of KBOs. Thermal evolution models of Centaurs can provide information on the possible structure of these bodies before their injection into the inner solar system. If Centaurs are covered by an organic crust, and if the crust survives, we can ask the following questions: How did the thermal history in the Kuiper belt influence their internal structure? What is the evolution of a differentiated Kuiper belt object when it arrives in the Centaurs' zone? Does the body still exhibit activity due to the residual presence of volatiles? We have computed the evolution of Centaur bodies assuming different parameters and initial conditions, with the aim of answering at least some of these questions. From the modeling of KBOs (*De Sanctis et al.,* 2001), we have verified that amorphous ice could be preserved for very long timescales even in the presence of long-lived radioactive elements. From these simulations, it was seen that Kuiper belt objects can be strongly depleted in hypervolatiles in the outer layers, down to several hundred meters below the surface. The resulting bodies are thus differentiated.

What is the evolution of such a body when it arrives on a Centaur-like orbit? According to *De Sanctis et al.* (2000), the evolution strongly depends on the dynamical path of the object. In the case of objects such as Pholus the dust flux, driven by gas activity, is negligible: Pholus does not develop a dusty coma. If Centaurs are bodies coming from the Kuiper belt, they should be partially differentiated and possibly covered by organic crusts. Pholus could be an example of this evolution. When a crust is present, gas molecules cannot flow freely through the dust layer, diffusing instead from the sublimation front through the crust. If we consider CO only in ice form (no gas trapped in amorphous ice), the CO flux depends on the depth at which CO ice is located. If CO ice is present several kilometers below the surface, gas emission is negligible and this kind of object can be considered inactive (with an activity level below the detection threshold). However, the volatile ices could still be present in the body under the organic crust; the gas flux is not sufficiently strong to remove dust particles from the surface (see Fig. 4).

Until recently, Chiron's activity was considered very unusual and induced by some "exotic" and "episodic" mechanism, such as outbursts due to crystallization (*Prialnik et al.,* 1995). The recent discovery of activity on some Centaurs, such as C/NEAT 2001 T_4, 174P/2000 EC_{98} (60558), P/2004 A_1 (LONEOS), and 2004 PY_{42} (*Epifani et al*., 2006; *Bauer et al.,* 2003), tells us that active Centaurs are quite common. We do not know if the activity is sustained by the same physical process for all these Centaurs, but in any case, we must begin to consider a possible common sublimation mechanism for all of them.

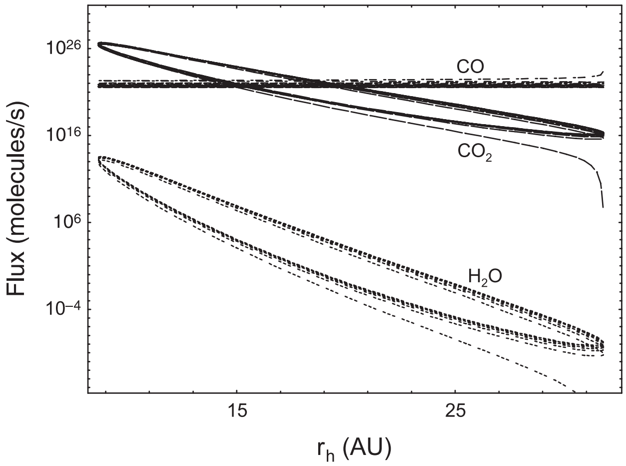

Fig. 4. Gas flux vs. heliocentric distance for Pholus model (from *De Sanctis et al.,* 2000).

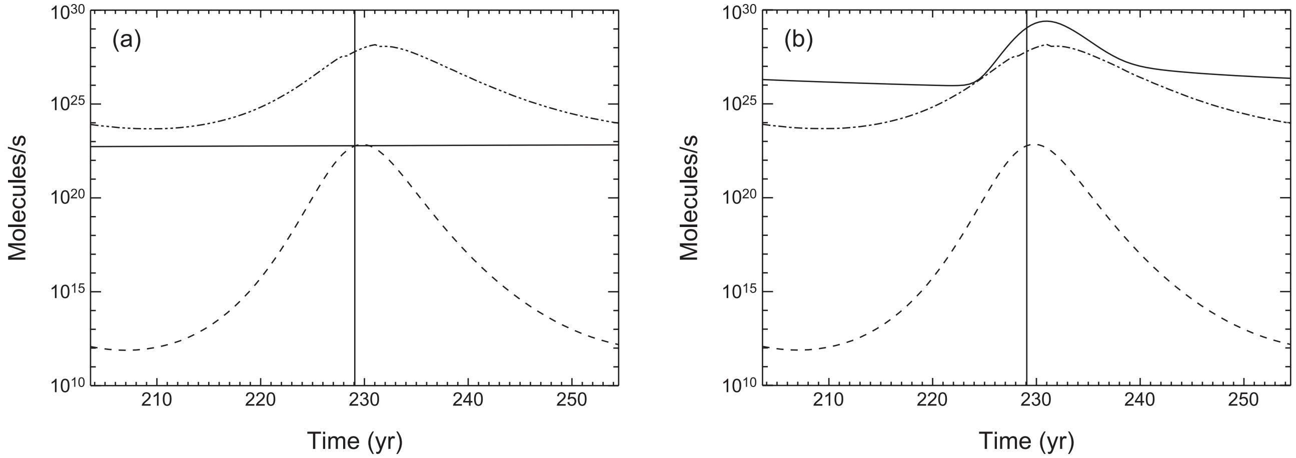

Fig. 5. Chiron models. **(a)** Gas fluxes from an old object when CO is not trapped in amorphous ice (line, CO; dash-dotted line, CO_2; dashed line, H_2O). **(b)** Same as **(a)**, but when the CO is trapped (from *Capria et al.,* 2000). The reason why some Centaurs are active and others are not is one of the main question about these class of objects, the answer to which can provide new and important constraints on the internal structure of KBOs.

Thermal models of active Centaurs indicate that the emission can be driven by volatile gas, as CO (*Capria et al.,* 2000; *Prialnik et al.,* 1995). Moreover, according to *Capria et al.* (2000), the present behavior of Chiron in terms of supervolatile (CO) emission can be explained only if the body is found in its present orbit with CO ice or CO gas trapped not too far from the surface (see Fig. 5). Given its probable origin in the Kuiper belt, Chiron should have arrived on its present orbit with the uppermost layers depleted of very volatile ices for a depth of some kilometers (*De Sanctis et al.,* 2001). If this is true, we could still explain observations of activity by supposing that water ice is mostly amorphous and some CO, trapped as a gas, is released at the transition to the crystalline phase. An alternative possibility could be some rejuvenation event, such as an impact or an orbit change, that ablated the first layers of the body. In any case Chiron should not have been on its present orbit for more than a few thousands of years. Chiron's activity implies that its internal structure preserves volatiles (trapped or as ices) in layers located not very far from the surface and that these layers must be at low temperatures.

The importance of Centaurs in the overall description of the evolution of icy bodies in the solar system is that they provide proof of the existence of a temporary storage of bodies, where they can undergo moderate thermochemical evolution. Further dynamical evolution can bring them either inside (giving origin to short-period comets) or outside the inner solar system.

6. OPEN POINTS

Given the previous discussion, we can state that the new observations available, the better comprehension of the dynamical evolution of the solar system through time (see all the work done in the framework of the "Nice Model"), and the efforts made in developing physically consistent models have allowed us to reasonably infer the overall behavior of icy bodies in the solar system and, in some cases, to predict the way in which activity develops; however, many open points still remain. In particular, we need to improve our knowledge in the following areas:

1. *Formation mechanism:* We have discussed the current theories of the formation of comets and KBOs, from which the overall chemical composition can be inferred; however, the formation mechanism mainly through binary collisions is very slow and the formation timescale is not sufficiently known to constrain the overall amount of short-lived radioactive elements that can be considered typical.

2. *Original composition and structure:* The amount of volatile elements is not known with accuracy, and can only be partially inferred for comets through their activity and the relative ratios of different gases. Cometary behavior became better understood when the concept of the diffusion of gases through a porous medium was developed. However, the interplay between macro- and microporosity in bodies with different sizes and overall strength is difficult to evaluate. It is also risky to assume that the composition of KBOs, Centaurs, and comets is the same. The path from KBO to comet is complex and partially unpredictable because of the role of impacts.

3. *Original mass distribution function:* The original mass distribution function is also related to the formation mechanism; however, this cannot be confirmed or disproved on the sole basis of observations due to the strong observational bias.

4. *Collisional evolution:* Collisional evolution can strongly modify the internal and surface evolution of different objects (*Orosei et al.,* 2001), but the energy distribution in a collision of icy bodies is not well known (*Durham et al.,* 2005).

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