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Thermal evolution models of Kuiper Belt Objects

M.C. De Sanctis[1], M.T. Capria[1], and A. Coradini[2]

[1] Istituto di Astrofisica Spaziale e Fisica Cosmica, Rome, Italy
e-mail: mariacristina.desanctis@iasf-roma.inaf.it
[2] Istituto di Fisica dello Spazio Interplanetario, Rome, Italy

Abstract. The outer solar system region, known as Kuiper Belt, should contain primitive bodies, probably among the most primitive objects of the solar system. They seem to be volatile rich objects showing strong relation to comets: the Kuiper belt is probably the source of most short period comets and Centaurs. The Kuiper belt objects could still contain ices and organic compounds with the same proportion as in the epoch of their formation from the primordial solar nebula. Thermal models of bodies moving on Kuiper belt orbits have been developed to follow their evolution and differentiation and to better understand the relations between them and the short period comets and Centaurs.

Key words. comets: general, Kuiper Belt, planets and satellites: formation

1. Introduction

The region beyond Neptune's orbit is populated with numerous, different bodies. This region, known as Kuiper Belt, should contain primitive bodies, probably among the most primitive objects of the solar system. They seem to be dark volatile rich objects showing strong relation to comets: the Kuiper belt is probably the source of most short period comets and Centaurs. A large number of observational results are now available on these bodies but we are beginning to see how these different populations are related to each other by dynamical and genetic relationships. In this paper we analyze the internal structure of the small objects that originated in the outer solar system, beyond Neptune. 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. It is 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. In this scenario, Centaurs, with their instable orbits, represent bodies in transition between Kuiper belt objects and the Jupiter family comets. 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 present structure and ap-

Send offprint requests to: M.C. De Sanctis

pearance 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.

In this paper we try to see what could be their thermal evolution and how and when it brings to their internal differentiation. In this paper the current status of our knowledge on the subject is reviewed, taking into account the results of thermal modeling.

2. Thermal evolution models

Many authors (Whipple and Stefanik 1996, Yabushita 1993, Haruyama et al. 1993, Prialnik et al. 1987, Prialnik and Podolak 1995) have studied the thermal evolution of cometary nuclei taking into account the radiogenic source using different thermal models and assumptions. Some of these works are devoted to the study of the thermal history of the comets during their residence in the Oort cloud, where the thermophysical conditions are very different from those in the Kuiper belt. These authors achieve very interesting results on the final internal structure of the Oort cometary nuclei and, as consequence, of the long period comets, but these results cannot be fully extended to the short period comets, being their origin and reservoirs very different. More recently, thermal evolution models of KBOs have been developed (De Sanctis et al., 2001, Choi et al., 2002, McKinnon et al, 2002) in order to understand the degree of thermal alteration suffered by bodies of Kuiper belt. 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 (De Sanctis et al, 2001, Choi et al., 2002) and models developed for icy satellites (McKinnon, 2002): 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.
In this paper we will focus our attention on the results obtained for the ”comet-like” thermal evolution models.

2.1. The ”comet-like” model

The model assume that the KBO are porous, low density objects and the thermal evolution is computed using a numerical code solving the unidimensional heat conduction and gas diffusion equations through an idealized spherical nucleus (De Sanctis et al. 2000, 2001, Capria et al., 2001). Due to the larger, with respect to comet nuclei, sizes of 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.
So, in this model we take into account also the radioactive heat process in addition to the others more ”convectional” described in the papers by (Coradini et al. 1997a,b, Capria et al. 1996). The composition and structure of comet nuclei are to the moment poorly known, and cannot be easily determined from ground observations. Parameters used in these simulations are derived from the observations, when available, or chosen between those that are considered typical for comets (Rickman,1994, Huebner et al., 1999). We developed different models to test different parameters and hypothesis (dust distribution, dynamical history, presence of trapped CO).
The model assumes that the body is homogeneous and uniformly porous, composed of ices and dust. The ices considered in these models are H_2O, CO_2 and CO, in different proportions: the most abundant molecule is water, while CO_2 and CO are representative of the more volatile species that have been observed in the coma of comets (Crovisier and Bockelée-Morvan 1997).
The dust grains, embedded in the ice matrix, are spherical and distributed among five different size classes. In these models we used an initial dust grain size distributions based on a

theoretical study of the dust grains accretion processes in the pre-solar nebula by Coradini et al. (1977).
Water ice is initially considered in amorphous phase, due to the very low temperatures at which these bodies are thought to form. In the Kuiper belt, far from the Sun, the thermodynamical conditions could keep the temperature low enough to preserve the amorphous ice. The model takes into account the phase transition from amorphous ice to crystalline ice (irreversible and exothermic).

The model accounts for external energy sources, the solar radiation reaching the surface, and internal, the radiogenic heating from the radioisotopes decay. The numerical code computes the heat diffusion in the porous material, leading to the H_2O ice phase transition and the sublimation of the volatile ices. The gases diffuse inside the pore system, either recondensing or escaping in space. The dust grains can be released by the sublimation of the ices and undergo the drag exerted by the escaping gas: the dust particles, depending on their sizes, can be blown off by the flux and lost in space, or they can accumulate on the nucleus surface to form a dust crust.

In the following we want to underline the main physical assumptions and the main differences (radiogenic heating) in respect to the previous model used for the models of Kuiper belt Objects. Major details on the thermal model adopted in this work are described in De Sanctis et al. (1999), Coradini et al. (1997a,b) and Capria et al.(1996).

3. The equations

The numerical code is written in spherical coordinates with radial dependence only, and the equations are solved for the whole nucleus.

The heat diffusion through the porous cometary material is described by the following equation, expressing the conservation of energy:

$$\rho c \frac{\partial T}{\partial t} = \nabla[K \cdot \nabla T] + Q_{H_2O} + Q_{CO_2} + Q_{CO} + Q_{tr} + Q_{rad} \quad (1)$$

where T is the temperature, t the time, K the heat conduction coefficient, ρ the density and c the specific heat of the comet material; Q_{H_2O}, Q_{CO_2} and Q_{CO} are the specific energies gained or lost due to sublimation and recondensation of the ices; Q_{tr} accounts for the energy released during the phase transition from amorphous to crystalline ice (Ghormley 1968) according to the activation law experimentally found by Schmitt et al. (1989); Q_{rad} is the energy released by the decay of radio isotopes and is described in the section below.
The product ρc is the average of the specific heats of the various components weighted by their masses in the unit volume. For the heat conduction coefficient of the porous cometary material we use Russel's formula, that takes into account both the solid phase and the pores (Espinasse 1989). In the models we do not take in account the advection by flowing gas: we have verified that advection is several order of magnitude below the conduction by the solid matrix.
The terms Q_{H_2O}, Q_{CO_2} and Q_{CO} of Eq. (1) are directly linked to the source terms Q^*_x of Eq. (2):

$$Q_x = -Po\ H_x\ Q^*_x \qquad [J\ m^{-3}\ s^{-1}] \quad (2)$$

where H_x is the latent heat of sublimation of component x and Po is the porosity. The equation describes the exchange of latent heat in sublimation-condensation processes in the elementary volume, where voids and ice molecules are present. The term Q_x accounts for the phenomena of sublimation-condensation to maintain the equilibrium between the solid phase and the gas phase at saturation condition. We refer to the elementary volume and the term Po is the porosity of this elementary volume.
The gas flow is described by the mass conservation equation:

$$\frac{\partial \rho}{\partial t} = -\nabla \Phi + Q^* \quad (3)$$

where ρ is the gas density, Φ its flux and Q^* the gas source term due to sublimation and recondensation processes. Due to the low pressures thought to exist within a comet nucleus (Steiner et al., 1990), we assume that gas density and pressure are related through the ideal

gas law, and the flow of each gas doesn't influence the others. The equation can be solved separately for each gas.
In our model we have made the assumption that the gas has a temperature equal to that of the solid matrix, because the perfect gas moving in the pore network has a thermal inertia negligible in comparison to the thermal inertia of the solid. The gas then reaches almost "immediately" the same temperature of the porous matrix in which it is moving or, more precisely, can reach the thermal equilibrium with the surrounding medium in a time scale that is much shorter than the characteristic time scale of the temperature variations in the solid matrix. In these physical conditions, the gas pressure variations do not affect the gas temperature, as the gas depends, for its temperature, much more on molecule-pore wall collisions rather than on molecule-molecule collisions. Therefore the equation that we solve is:

$$\frac{1}{RT}\frac{\partial P_x}{\partial t} = \nabla[G_x \cdot \nabla P_x] + Q_x^*. \qquad (4)$$

where R is the universal gas constant.

In a quasi-stationary regime, Φ can be written as

$$\Phi_x = -G_x \nabla P_x \qquad [mol\, m^{-2}\, s^{-1}] \qquad (5)$$

where P_x is the partial pressure of gas x, and G_x its gas diffusion coefficient.
The diffusion regime depends on the mean free path of the molecules in the pore system and has been studied in detail by Espinasse et al. (1991), who gave also the expressions for $G(T, P)$ when the mean free path of molecules is larger or smaller than the diameter of the pores. Q_x^* is the gas source term, i.e. the source of matter. Since we consider a three components ice mixture, the equation (4) must be solved three times. Q_x^* has been set to zero in all the layers of the comet where no solid phase was present: in these layers the solution of equation (4) gives the pressure. When the component x is present in the solid phase, under the assumption that the system reacts instantaneously to pressure or temperature variations, the term Q_x^* can be written as follows:

$$Q_x^* = \frac{1}{RT}\frac{\partial P_x}{\partial t} - \nabla[G_x \cdot \nabla P_x]\ [mol\, m^{-3}\, s^{-1}] \qquad (6)$$

in which it is assumed that the partial pressure of component x is equal to the saturation pressure. Only in this case the equation (4) is not solved. The source term Q_x^*, that takes into account the sublimation and condensation phenomena of the gas component x, is also the source term of the heat equation when multiplied by the latent heat of sublimation and condensation. In our model the diffusion equations are solved only inside the pore network, where, as we already stated, it is possible to ignore the thermal capacity of the gas component. In these conditions, the computation of Q_{H_2O}, Q_{CO_2} and Q_{CO} is only needed to know the amount of sublimating and condensing volatiles; actually the results reported by Steiner et al. (1990) on the results of KOSI experiment show that the energy of the convective transport is much smaller than the sublimation - condensation energy.

The surface boundary condition for Eq. (1) is obtained by computing the energy balance at the surface of the comet, while at the centre of the comet the condition is:

$$\frac{\partial T}{\partial r} = 0 \qquad (7)$$

The surface boundary condition used to solve the diffusion equation Eq. (2) when a dust crust is present is obtained assuming that the pressure vanish at the surface. In this case we think that the gas can flow freely through the dust crust.

$$P_x = 0 \qquad (8)$$

The surface boundary condition used to solve the equation when ice is present on the surface is:

$$P_x = P_x^{sat}(T) \qquad (9)$$

The centre boundary condition is obtained by assuming that the ice is in equilibrium with its vapor, and the partial pressures are equal to the saturation pressures at the temperature of the solid matrix.

3.1. Radiogenic Heating

For the radiogenic heating, we consider the effects of ^{40}K, ^{232}Th, ^{235}U,^{238}U radioisotopes, and in one case of ^{26}Al.
The rate of radioactive energy release, Q_{rad}, is given by

$$Q_{rad} = \rho_{dust} \Sigma \lambda_j X_{oj} exp^{-\lambda_j t} H_j \qquad (10)$$

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. To model the thermal evolution of these bodies we must make some assumptions regarding the heat generated by radio-decay.

For the radioactive elements we assume that the abundance of ^{40}K, ^{232}Th, ^{235}U,^{238}U are in the same proportion as in the C1 chondrites (Anders and Grevesse 1989).
The values of ^{40}K, ^{232}Th, ^{235}U,^{238}U are taken from Robert 1984, for ^{26}Al from Brown et al. (1986). We take X_{oj} as the mass of the $j'th$ radioisotope per unit mass of C1 chondrites extrapolated back to $4.5x10^9$ years ago when the comets are supposed to be formed (Whipple and Stefanik 1966).

4. Results

We have applied the model to a typical Kuiper Belt body and have simulated its evolution.

4.1. Low density bodies

In these models we consider KBOs as very porous, low density objects (density similar to the comet nuclei) and we account for CO as representative of the more volatile ices inventory. The main common result for all the models is the depletion of the most volatile ices (like CO). 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(fig.1).This temperature increase is reflected in the degassing of high density KBO that proceeds faster than for icy bodies

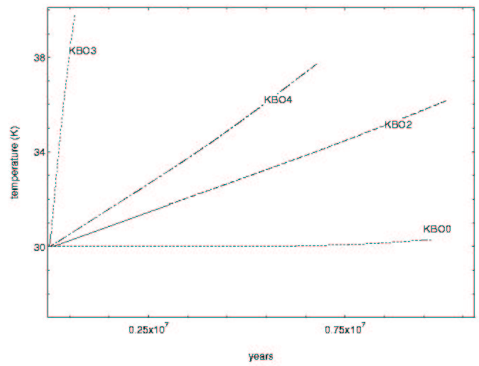

Fig. 1. Variation of the central temperature. KBO0 is the reference model without radioisotopes; KBO2 is the case with only long lived radioisotopes and the same amount of dust and ice (dust/ice=1); KBO3 is the case with long lived radioisotopes and ^{26}Al; KBO4 is the case with only long lived radioisotopes and a dust/ice=5.

The main result is that the Kuiper Belt Objects can be strongly volatile depleted bodies. In the upper layers, several hundred meters below the surface, the most volatile ices (like CO) are completely absent. However, deeper in the structure, also regions enriched in volatile ices are formed, due to the re-condensation of volatiles in cooler layers.
Due to radiogenic heating the internal temperature may become high enough to permit the sublimation of CO also from the inner layers. The result of these processes is that the KBOs shall be very differentiated: typically, interlaced layers of CO-depleted and CO-enriched can be found (De Sanctis et al., 2001).
The evolution of such a body when injected in the inner Solar System will be characterized by outbursts of volatiles, when the volatiles enriched layers reach the sublimation temperature.

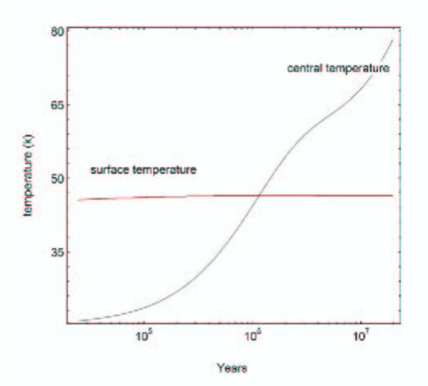

Fig. 2. Variation of the central temperature and surface temperature for "Phoebe-like" model.

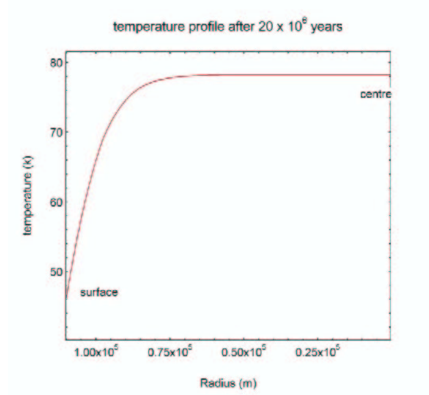

Fig. 3. Temperature profile for "Phoebe-like" model after $2x10^7$ years.

However, from these simulations it can be seen that an undifferentiated core can survive, depending mainly on the kind and amount of radiogenic elements considered in the body, but also on the physical parameters assumed, such as thermal conductivity, porosity, radius, etc.

4.2. Medium density bodies

If we assumed larger density, similar to Phoebe density, we can see that alteration due to the radioisotopes is much more than in the previous case. Considering a small amount of ^{26}Al and the other long lived radionuclides, we have seen that the internal temperature is higher than before. In fig. 2 is reported the evolution of the central and surface temperatures. The interior of a body (fig. 3) like that can be strongly affected by this temperature increase with the loss of the hypervolatile ices and, possibly, the water ice transition.

According to our results, bodies like that, due to the large amount of dust with respect to ice, can be deeply altered by the presence of short lived radioisotopes in the refractory component. However, the kind and the amount of the radioisotopes is the most important parameters that affects the results.

5. Discussion and conclusion

KBO models can give very different outcomes depending on the assumptions made such as ice fraction in the initial composition, the amount and the kind of radioisotopes, the object structure, the dimension, the thermal conductivity. These factors affect the evolution in different ways.
The amount and kind of radioisotopes provide different heating in different period of time. The ^{26}Al is a very intense heat source, that can rise the temperature in a relatively short period of time. The amount of this radioactive element strongly influences the body evolution.
The total amount of radioisotopes is function of the dust in the nucleus. The presence of dust is a key parameter: the larger is the dust amount, the larger is the radio heating. At the same time, the dust affects on the overall thermal conductivity: the larger is the dust/ice ratio, the larger is the thermal conductivity. The combination of these two effects strongly increases the overall process of heat transfer.
The composition, especially the nature of water ice, has influence on 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 in particular conditions (very low conductivity), gives a run-away increase of internal temperature.

The structure of the nucleus, in terms of porosity and pores radii, has strong influence on the thermal conductivity and, consequently, on the internal temperature. Porous media are inefficient conductors. Low conductivity results in higher temperature. The dimension of the nucleus is important. Earlier works have shown that the radio-heating is not efficient for small bodies. Naturally, the overall thermal conductivity influences strongly the final results. All these parameters act in different ways on the comet thermal evolution and different combinations of these parameters can lead to very different results. The upper-size limit and density 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. 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.

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