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Thermal Evolution of Comet P/Tempel 1—Representing the Group of Targets for the *CRAF* and *CNSR* Missions

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The properties of the outer layers of comets considered for the future *Comet Rendez-vous and Asteroid Flyby* and *Comet Nucleus Sample Return* missions are studied, by following numerically the thermal evolution of spherically symmetric models of the nucleus, in the orbit of Comet P/Tempel-1. The evolution starts from isothermal (10°K) and homogeneous nuclei, composed of amorphous ice and dust. The crystallization of amorphous ice at 137°K is taken into account. As the ice sublimates, a permanent dust mantle is allowed to accumulate, at a rate which is proportional to the sublimation rate. Evolutionary sequences are computed for different values of the density, the dust/ice mass ratio, and the (constant) fraction of the dust which is not carried away with the sublimating ice. The main conclusions are (a) the temperatures at the outer and inner surfaces of the dust mantle are not very sensitive to changes in the parameters; (b) although the dust is assumed permeable to water vapor, the rate of erosion of the nucleus slows down as the dust mantle grows and its insulating effect increases; (c) the temperature at a depth of 10 m is ~160°K for all models considered and hence, the ice at this depth is crystalline; (d) the total thickness of the crystalline ice layer, between the dust mantle and the amorphous ice core, varies from 40 to 240 m, depending on the parameters assumed. Consequently, it should be difficult for the probes of the two comet missions to sample pristine amorphous ice, unless they are aimed at the bottom of an active crater.

I. INTRODUCTION

In the wake of the several successful Comet Halley flybys and in view of the extremely exciting findings of these missions, the community of comet scientists is planning additional missions: CRAF (Comet Rendez-vous and Asteroid Flyby) and CNSR (Comet Nucleus Sample Return). In the first (Spinrad 1987), a probe will be launched into a cometary nucleus to analyze its composition and structure over a period of several days. The second mission (Wood 1987) is even more ambitious: it involves landing on a comet nucleus, digging into its upper layer, collecting ice and dust samples, and returning them (in a suitably refrigerated state) for study in terrestrial laboratories. Both missions are expected to greatly advance planetary science, by providing detailed information on *pristine* planetary material and planet-forming processes in the outer Solar System. They might also link comets with dense interstellar clouds.

Out of the huge number of known comets, the ones most suitable for these missions are those with small inclinations and perihelia at less than ~2.5 AU, because propulsion requirements become excessive outside this region. Thus, a rather limited number of comets are accessible, those with a semimajor axis (a) between 3.0 and 6.3 AU, an eccentricity (e) between 0.15 and 0.78, and a perihelion distance (q) between 1.3 and 2.6 AU (Wood 1987).

A detailed knowledge of the physical conditions prevailing in the outer layers of these comets—which will be penetrated by the probes—is obviously essential for the

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CRAF and CNSR missions. Cometary nuclei are expected to be coated by a continuously growing dust mantle. Such a dust mantle is thought to be responsible for the low activity of some comets, e.g., P/Encke. However, following the observations of Giotto and Vega on P/Halley, which is a very active comet, it appears that much of its surface is covered by a hot, dark layer of insulating dust as well. Hence an outer permanent dust mantle is probably a common feature of comets. Its thickness is still, however, an open question. Even more important to the CRAF and CNSR missions is the question of whether near the surface the ice is amorphous or hexagonal. In the former case, the ice may trap large quantities of gas inside its numerous pores, whereas in the latter, the gases are trapped only as clathrate–hydrates and, possibly, in gas pockets (cf. Prialnik and Bar-Nun 1987, Laufer *et al.* 1987). All the short-period comets considered for these missions have already completed many revolutions around the Sun. Thus, if they started as homogeneous bodies of dust and ice in the amorphous form, the outer layers have already been heated above 137°K and the ice has transformed into crystalline (cubic and then hexagonal) form. The main question we address in this paper is to what depth does the crystalline ice layer extend and what are the chances of the digging equipment (Clark *et al.* 1986) to sample pristine, amorphous ice, or thermally processed, crystalline ice.

Our main assumptions and choice of parameters are presented in Section II; in Section III the results of the numerical simulations of a comet's model evolution are described; a brief discussion and conclusions follow (Section IV).

II. ASSUMPTIONS AND PARAMETERS

The purpose of the present paper is to follow the evolution of a typical comet nucleus model, in the spherically symmetrical ("fast rotator") approximation, for a *large* number of revolutions in a very short-period comet orbit. Long-term, secular changes in the average temperature profile and the composition of the nucleus are sought. Orbital, short-term variations of the temperature and the gas and dust output for short-period comets have been studied by Fanale and Salvail (1984).

The initial model of all the numerical simulations has a radius R_0 of 5 km, a uniform temperature of 10°K, and a homogeneous composition of amorphous ice and dust. The orbit of Comet Tempel-1 is chosen as representative of the orbits considered for the CRAF and CNSR missions. It has a period of 5.5 years, an eccentricity of 0.52, and a perihelion distance of 1.5 AU.

Several parallel evolutionary sequences are computed, spanning more than 100 revolutions, for various combinations of the following parameters:

1. The density of cometary material. Two values of the density parameter ρ, defined as a fraction of 1 g cm^{-3}, are adopted: 0.2 and 0.55. The former should be considered a lower limit (Rickman 1986), while the latter is an average value (Sagdeev 1988), both obtained from the P/Halley data gathered by the Giotto and Vega spacecraft.

2. The dust to ice mass ratio. The mass fractions of ice and dust are denoted by X_i and X_d, respectively. The cases considered are $X_d/X_i = 1$ (Delsemme 1982, Greenberg 1982) and $X_d/X_i = 0.2$ (within the range obtained for Comet P/Halley, Mazets *et al.* 1986).

3. The fraction of the dust mass which is assumed to accumulate on the surface of the nucleus (while the rest of the dust is carried away with the sublimating ice). This fraction is denoted by η (cf. Prialnik and Bar-Nun 1988), where $0 < \eta < 1$. We have considered the values $\eta = 0.001$, 0.01, and 1. The lowest value implies a very slow growth of the dust mantle, whereas $\eta = 1$ is an extreme (essentially academic) case, which yields an upper limit to the rate of mantle growth. The rate of growth of a permanent dust mantle depends critically on the size distribution of the dust grains, in particular on the size of a grain in equilibrium at the surface—which can be inferred from observations—and on the maximal grain size—which is completely unknown. An approach meant to circumvent this difficulty is the "friable sponge" model proposed by Horanyi *et al.* (1984), where the size distribution of the grains in the mantle is assumed to remain *constant* with time. Thus, particles of *all* sizes are removed from the surface at the same rate, which might require that the largest grains be broken into smaller ones (i.e., friability). A still different approach, adopted by Fanale and Salvail (1984, 1986), following Brin and Mendis (1979), is to assume an *arbitrary* (universal) maximal grain size (say, 1 cm radius). In this case, the dust mantle thickness depends on orbital parameters. In the present study we refrain from ad hoc assumptions regarding the sizes of dust grains and adopt η as an unknown free parameter. It should be noted that the constant η assumed in each case represents an *orbit averaged value*. Calculations which were concerned with the variation of the dust mantle's thickness *within* one revolution have shown that η is smaller preperihelion and larger postperihelion (e.g., Podolak and Herman 1985).

We shall not investigate the outcome of *all* possible combinations of the values assumed by these three initial parameters, but only the most relevant ones. The results will be presented schematically in the three-dimensional parameter space shown in Fig. 1a.

The one-dimensional code used in these calculations was described in detail by Prialnik and Bar-Nun (1988). It allows for the crystallization of amorphous ice (Prialnik and Bar-Nun 1987) and for the formation and growth of an outer, permanent, dust mantle. Adopting the mass m within a sphere of radius r as the independent space variable, the thermal evolution equations for a spherical comet are

$$\partial u(m, t)/\partial t = \partial F(m, t)/\partial m + q(m, t), \quad (1)$$

where the internal energy per unit mass $u(m, t)$, for a mixture of ice and dust, is related to the temperature $T(m, t)$ by

$$u(T) = \int_0^T (X_i c_i(T') + X_d c_d) dT'. \quad (2)$$

The heat capacity of ice, either amorphous or crystalline, is given by Klinger (1981) in the form $c_i(T) = 7.49\ 10^4 T + 9\ 10^5$ ergs g^{-1} °K^{-1}. The heat capacity of the dust component is assumed constant, $c_d = 7.7\ 10^6$ ergs g^{-1} K^{-1}, a value typical of meteoritic material (Wood 1963). The heat flux $F(m, t)$ is given by

$$F(m, t) = \kappa(T)\partial T(m, t)/\partial m, \quad (3)$$

where $\kappa(T) = p(4\pi r^2)^2 \rho [X_i K_i(T) + X_d K_d(T)]$. The thermal conductivity of amorphous and crystalline ice is given by Klinger (1980); for the dust we adopt the formula given by Mendis and Brin (1977). The factor p, of order 0.5, takes approximate account of the porosity. The boundary conditions for F are zero flux at the center and the difference between absorbed solar radiation and emitted thermal radiation at the surface. The term $q(m, t)$ represents heat sources and sinks, such as crystallization or sublimation. The rate of mass loss from the comet is thus given by

$$\dot{M} = -4\pi R^2 \mu Z(T)[X_i + (1 - \eta)X_d], \quad (4)$$

where μ is the mass of a water molecule and $Z(T) = P(T)/\sqrt{2\pi\mu k T}$ is the sublimation rate, as determined by the vapor pressure $P(T)$. Finally, the (average) thickness of the dust mantle Δr_d, at any time t, is given by integration from $t = 0$ ($\Delta r_d = 0$),

$$\Delta r_d = \frac{\eta \mu X_d}{\rho_d} \int_0^t Z[T_i(t')] dt', \quad (5)$$

where ρ_d is the dust density and T_i is the temperature at the ice surface (below the dust mantle). We point out that our models are not meant to provide an accurate picture of the comet's dust mantle at a given time and a given point of the orbit, but its average thickness and characteristic tem-

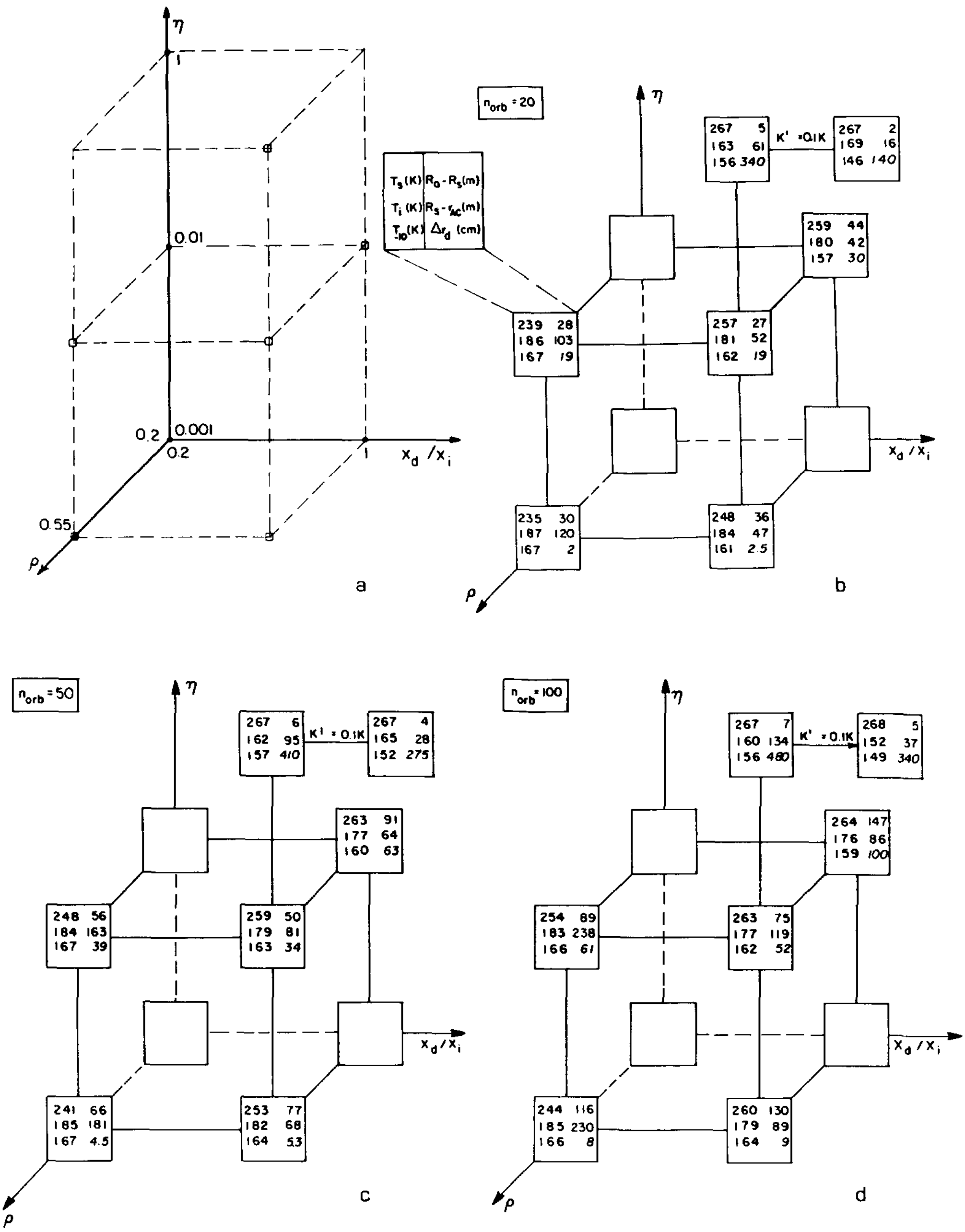

FIG. 1. (a) Schematic representation of the three-dimensional parameter space (ρ, X_d/X_i, η) investigated. Calculations are performed for two values of ρ, 0.2 and 0.55 g cm^{-3}; two values of X_d/X_i, 0.2 and 1; and three values of η, 0.001, 0.01, and 1. Small squares correspond to the combinations of parameters adopted in each of the computed evolutionary sequences. Results of the evolutionary calculations are given for the perihelion of (b) the 20th orbit, (c) the 50th orbit, and (d) the 100th orbit. The meaning of the six numbers appearing in each square panel is shown in the separate (larger) square panel. For the meaning of symbols, see text.

perature range, expected to develop with repeated revolutions.

III. RESULTS OF EVOLUTIONARY CALCULATIONS

Apart from the three uncertain (or unknown) parameters already mentioned, another unknown factor, which is expected to affect the structure of a cometary nucleus, is its age—the time elapsed since the comet entered the inner Solar System. As we are interested here mainly in secular changes in a comet's structure, the relevant unit of time is one orbital period (in our case 5.5 years). Comet P/Tempel-1 was first observed in 1866 (Hawkins 1964) and, therefore, has completed at least 20 revolutions.

Results of the evolutionary calculations for the perihelia of the 20th, the 50th, and the 100th orbits are given in Figs. 1b–d. Each square panel corresponds to a set of three parameters (ρ, X_d/X_i, η), as shown in Fig. 1a. The numbers in the left column of each panel are temperatures (in °K) at three different points: T_s, at the surface of the dust mantle; T_i, at the surface of the icy core below the dust mantle; T_{-10}, at a depth of 10 m below the surface. The numbers in the right column are $R_0 - R_s$ (in meters), the difference between initial radius and surface radius at a given orbit (or, the thickness of ice that has been lost by sublimation); $R_s - r_{AC}$ (in meters), the difference between surface radius and the radius of the interface between crystalline and amorphous ice (or, thickness of the crystalline ice layer overlying the inner core of amorphous ice); Δr_d (in centimeters), the estimated thickness of the dust mantle.

The following conclusions may be drawn from these results:

1. The temperature at the surface of the dust mantle is very weakly dependent upon the assumed parameters. Thus, the perihelion value of T_s varies in the range between 235 and 268°K, corresponding to an average value: $\bar{T}_s = 252 \pm 17$°K. The perihelion temperature depends, of course, on the assumed values of the fixed parameters: albedo (0.04) and emissivity (0.5). A higher emissivity, for example, would result in lower surface temperatures, but those would still be weakly dependent on the parameters investigated here.

2. The dependence of the temperature at the icy-core/dust-mantle interface on the assumed parameters is even smaller. This is due to the extreme temperature sensitivity of the sublimation rate controlling it. The perihelion value of T_i is found to be between 176 and 187°K, except for the extreme case when $\eta = 1$.

3. For all models, there is a very slow increase in surface temperature (T_s) and decrease in interface temperature (T_i) at all points of the orbit, with repeated revolutions. This is illustrated in Fig. 2, where the variations of T_s and T_i with heliocentric dis-

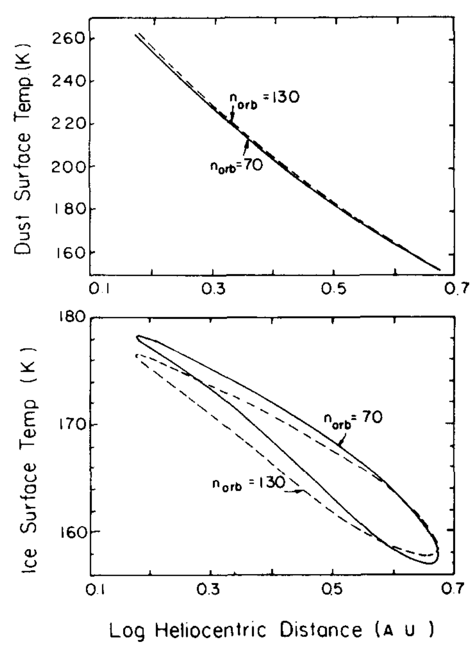

FIG. 2. Variation of the dust mantle's surface temperature (upper panel) and of the ice surface temperature, below the dust mantle (lower panel) with heliocentric distance, in the orbit of Comet P/Tempel-1, for the 70th (solid line) and 130th (dashed line) revolutions. Other parameters are $\rho = 0.55$ g cm^{-3}, $X_d/X_i = 1$, and $\eta = 0.01$. Note the difference between the upper and lower temperature scales.

tance are given for the 70th and the 130th orbits of the ($\rho = 0.55$, $X_d/X_i = 1$, $\eta = 0.01$) model. It is noteworthy that the *orbital* temperature variation (perihelion vs aphelion) for the ice surface amounts to only ~20°K, while for the dust mantle it is ~110°K. The reason for the slow shift in the T_s and T_i orbital variation with increasing number of revolutions is the gradual growth of the insulating dust mantle. A larger fraction of the absorbed solar energy is retained by this mantle, raising its temperature (and thus T_s). Therefore, a diminished heat flux reaches the ice surface, resulting in a lower T_i.

4. The temperature at a depth of 10 m is practically constant in time for each set of parameters. Moreover, it varies very little from one set of parameters to another. Thus we may expect the temperature at this depth to be 163°K with an uncertainty of ~3% (within the assumptions inherent to our numerical simulations). The lowest limit for T_{-10}, set by $\eta = 1$, is ~150°K. *Hence we can hardly expect to find amorphous ice at a depth of 10 m below the surface.*

5. Deeper down into the comet, the heating process is very slow and thus the *initial temperature is preserved throughout most of the comet's mass*. For example, for the ($\rho = 0.55$, $X_d/X_i = 0.2$, $\eta = 0.001$) model, where the dust insulation is minimal, changes in temperature occurred only down to 230 m below the surface (i.e., ~5% of the radius, or ~13% of the mass) during the first 55 revolutions. After another 55 revolutions (110 in all), the thermally affected region extended down to 320 m below the surface (i.e., ~7% of the total radius, or ~18% of the mass). This justifies our choice of a very low initial temperature (10°K). Such a temperature would be typical of comets which—regardless of their place of formation—spent a very long period of time in the outer Oort cloud, before entering the inner Solar System. Presumably, hundreds of orbits (within the Solar System) were required for a short-period comet to be perturbed to its present orbit. In the process, one could expect its interior to have been heated, perhaps to much higher temperatures. However, even if (hypothetically) the comet were thrown into its present orbit directly from the Oort cloud (as implied here), our results show that one (or several) hundred revolutions would not have altered the interior temperature significantly. Hence a *low initial temperature* is a reasonable assumption, *provided the cometary ice is amorphous.*

6. As expected, the decrease in the nucleus' radius is more significant when a lower bulk density is assumed. To lowest approximation, the thickness of sublimated ice is inversely proportional to ρ. Regardless of the dependence of $\dot{R}_s$ on ρ, we find that for each evolutionary sequence—given ρ—the decrease of the surface radius slows down with time. Thus, for example, for the sequence ($\rho = 0.55$, $X_d/X_i = 0.2$, $\eta = 0.01$) the average $\dot{R}_s$ is 1.4 m/orbit for the first 20 orbits, then 0.93 m/orbit for the next 30 orbits, and, finally, 0.66 m/orbit for the following 50 orbits. This is due to the increasing insulating effect of the dust mantle. These rates of erosion are obtained on the assumption that the dust mantle is at all times permeable to water vapor. In reality, the permeability should decrease as the mantle thickens, and the insulating efficiency of the dust mantle should improve. Moreover, new experimental results on large ice samples (Benkhoff and Spohn 1988) show that some of the water vapor migrates back into the ice, forming an ice crust of higher density and thermal conductivity. Thus, the rate of erosion may decrease even more rapidly, because of the more efficient heat conduction into the interior. Ultimately, we expect the nucleus' surface to become extinct, except for accidental patches of exposed ice.

7. According to our models, the crystalline ice shell overlying the inner core of gas-laden amorphous ice is at least 40 m thick and may well be as thick as 240 m. The crucial parameter in this respect is the dust

to ice ratio. The higher this ratio, the thinner the crystalline ice layer becomes (cf. Prialnik and Bar-Nun 1988). The average rate of advance of the crystallization front into the amorphous ice core is higher than the rate of erosion of the nucleus. Therefore, the depth of the crystalline ice/amorphous ice interface increases with time. This trend is illustrated in Fig. 3 for the ($\rho = 0.55$, $X_d/X_i = 1$, $\eta = 0.01$) model.

8. The thermal conductivity of ice and dust mixtures is not known experimentally. The conductivity of ice at low temperatures is given by Klinger's (1981) empirical formulae. That of the dust is based on theoretical models (e.g., Mendis and Brin 1977, Brin and Mendis 1979). A mass averaged value is adopted here for mixtures of the two (see Section II). It has been recently claimed, however, that the thermal conductivity of cometary material could be much lower (Squyres *et al.* 1985). In order to examine the effect of the assumed thermal conductivity on the results, we ran a test model, with the thermal conductivity coefficients arbitrarily lowered by a factor of 10. Our aim was to find a lower limit for the thickness of the outer crystalline ice layer. Therefore, we adopted for the trial run the parameters expected to minimize the thickness of such a layer ($\rho = 0.55$, $X_d/X_i = 1$, $\eta = 1$). The results are shown in Figs. 1b–d in a panel adjacent to that corresponding to the same set of parameters and unaltered conductivity. We conclude that only in the case of a very dusty material of extremely low thermal conductivity which, in addition, grows rapidly a thick dust mantle, might we find amorphous ice at a depth of less than ~20 m below the surface (Fig. 1b).

9. Obviously, the *rate of growth* of the dust mantle is almost solely determined by the parameter η, which is practically unknown (see discussion by Prialnik and Bar-Nun 1988). The *thickness* of the dust mantle—of a given comet at a given time—depends on the number of revolutions already completed. As Comet P/Tempel-1 has completed more than 20 revolutions,

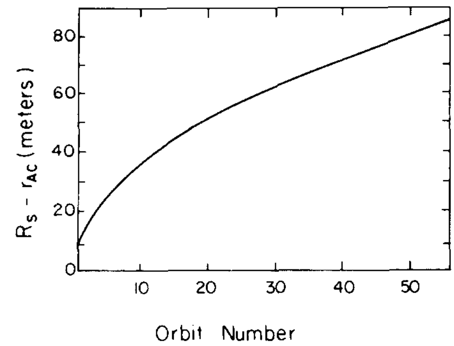

FIG. 3. Variation of the thickness of the crystalline ice layer overlying the amorphous ice core, during the first 55 revolutions in the orbit of Comet P/Tempel-1. The model parameters are the same as in Fig. 2.

the numbers given in Fig. 1b should represent limiting values for its expected characteristics. Unfortunately, no definite prediction can be made for the thickness of the dust mantle (Δr_d), since—depending on the value of η—the mantle could be as thin as 2 cm, or as thick as a few meters (as $\eta \rightarrow 1$). Further complications regarding the estimate of the dust mantle thickness arise from its unknown composition and, therefore, density. The present evaluations assume a dust mantle density of 0.8 g cm^{-3}, as suggested by Weissman (1987). A lower density would imply a lower heat conductivity (discussed above) and, probably, a thicker and fluffier dust mantle.

IV. DISCUSSION AND CONCLUSIONS

We simulated the evolution of a spherically symmetric comet nucleus in P/Tempel-1's orbit for a variety of parameters. Our object was to study the propagation of the crystallization front into the nucleus, in an attempt to estimate the extent of the crystalline ice shell that presumably encloses an amorphous ice core. We found this thickness to be between 40 and 240 m, depending on the parameters assumed and the number of revolutions already completed. These results should not be significantly altered by the adoption of other orbits considered for the CRAF and CNSR missions, all of which have perihelia ≤2.5 AU. Although the dust temperature is very sensitive to the heliocentric distance d, the temperature at the ice surface below the dust mantle, $T_i(d)$, *becomes slowly dependent upon* d, *when* $d \leq 2.5$ *AU*. At this distance, comets become exceedingly active and the ice surface temperature is mainly controlled by the sublimation rate. This $T_i(d)$ behavior is confirmed by the orbital variation of the surface temperature obtained in pure ice models for Comet P/Halley between ~2.5 AU and the perihelion, 0.587 AU (e.g., Prialnik and Bar-Nun 1987). The thermal evolution of the nucleus, in particular the phase transition from amorphous to crystalline ice that takes place in its interior, are determined by the temperature at the surface of the ice core. Therefore, our results should remain valid for all orbits of similar period and $q \leq$ 2.5 AU.

Since even the lower limit of 40 m, obtained for the thickness of the crystalline ice crust, is significantly larger than the depth currently planned for the CRAF and CNSR probes to reach (e.g., Clark *et al.* 1986), we may conclude that the probes will, in all probability, sample crystalline ice. If the target comet resembles P/Halley, where several active craters were found, then it might be worthwhile to dig into such a crater, at the bottom of which the more active, gas-laden amorphous ice should be exposed.

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