ken, confirms for the first time in a more quantitative way the likely presence of water ices or snows in comets and the three-step mechanism of production of OH and H. It seems very difficult to keep a three-step mechanism by using something other than water. Direct desorption of radicals would give a two-step process with $n = -4$ or less. Dissociation of larger molecules would give, by and large, at least one more step for either H or OH. When better observations are known, it is hoped that mechanisms of this type will explain the physical processes and the origin of the other radicals observed in cometary heads.

A. H. DELSEMME

Ritter Astrophysical Research Center, University of Toledo, Toledo, Ohio 43606

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Satellites of the Outer Planets: Thermal Models

Abstract. *Steady-state thermal models for the large satellites of the outer planets strongly indicate that their interiors are currently maintained at temperatures well above the ice-ammonia eutectic temperature by the decay of long-lived radioisotopes of potassium, uranium, and thorium. The present-day steady-state thermal structure of a representative satellite, J IV (Callisto), is shown to be characterized by the presence of a thin icy crust over a deep liquid mantle, with a dense core of hydrous silicates and iron oxides. Some dynamical consequences of this model are briefly discussed.*

It is well established that several large satellites of the outer planets have densities near 2 g cm^{-3}, approximating that of a mixture of the rock-forming and ice-forming elements in solar proportions (*1*). Both the available observational data (*2*) and current theories for the origin of the solar system suggest that temperatures at and beyond Jupiter's orbit were low enough to be within the stability field of common ices during the accretionary era. Thus the abundant elements would be found in those chemical compounds that are stable in the presence of a cold, low-pressure gas of solar composition (*3*). Because of the stability of hydrates of ammonia and methane at low temperatures, substantial quantities of these gases may be retained by a condensate formed 50° or more above the condensation temperatures of pure ammonia or methane (*4*).

It is clear that the rate of heat production from the radioactive decay of a solar-proportion mixture of ices and silicates (which is about two-thirds ices by mass) will be much slower than that for a chondritic object, but the possibility of interesting chemical and physical consequences of such mild heating should not be dismissed out of hand. In order to effect large-scale differentiation of the interior of a large satellite such as J IV (Callisto) one need only reach the eutectic temperature in the NH_3-H_2O system. The temperature at which the eutectic melt appears is 173°K [by comparison, Callisto's daytime surface temperature, as found by infrared emission measurements, is 160°K (*5*)]. This raises the possibility that the interiors of the Galilean satellites of Jupiter and the larger satellites of the other outer planets may be extensively melted, and hence may have undergone differentiation of the icy and rocky components.

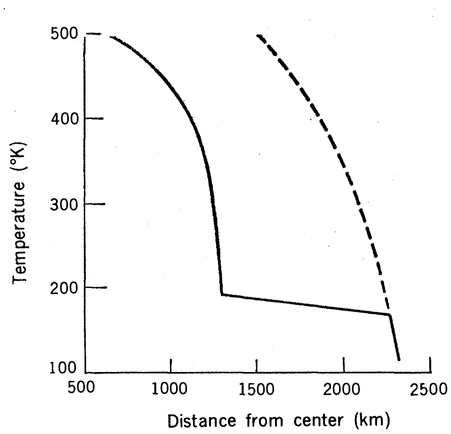

Fig. 1. Approximate present-day interior temperature profiles for Callisto (J IV). The dashed line describes a fictitious object in which melting does not occur, whereas the solid line gives an approximate profile for an object in which the known melting behavior of the NH_3-H_2O system is incorporated. A mean surface temperature of 110°K has been used for both models.

I shall describe briefly a steady-state thermal model for J IV in which the present-day heat production by the decay of ^{40}K, U, and Th is exactly equalled by the net radiative loss from the surface. The heat balance equation for the surface regions is

$$K \frac{\partial T}{\partial Z} = S\rho R$$

where K is the thermal conductivity (*6*), $\partial T/\partial Z$ is the vertical temperature gradient near the surface, S is the present-day rate of heat production, ρ is the density, and R is the radius of the satellite. The present-day value of S for chondritic material is 5×10^{-8} erg g^{-1} sec^{-1} (*7*), and thus a solar-proportion mixture of chondritic material with ices, which is three times as massive as the chondritic component, will have $S = 1.7 \times 10^{-8}$ erg g^{-1} sec^{-1}. The difference between the central and surface temperatures varies roughly as R^2. For a solar-proportion mixture of the rock-forming and ice-forming elements at accretion temperatures above the condensation point of CH_4, the condensate is about 54 percent H_2O, 15 percent FeO, 13 percent SiO_2, 10 percent NH_3, and 8 percent MgO (by mass). These major components mixed in the proportions given would give a bulk density at zero pressure of about 1.8 g cm^{-3}, in good agreement with the observed density of about 2.0 g cm^{-3} found for J IV.

An instructive but very imprecise calculation of the temperature profile in J IV may be made by using the thermal conductivity of an ice-silicate mixture extrapolated up to temperatures and pressures at which ice I is no longer stable. In such a model no consideration is given to known phase transitions, but the model is instructive in that it shows that the large temperature gradient calculated for J IV (about

1°K km near the surface) requires quite high central temperatures. The dashed curve in Fig. 1 presents the results of this calculation. A physically realistic model of J IV, in which known phase transitions in the NH_3-H_2O system are allowed for, is given as the solid curve in Fig. 1. Here the temperature gradient is calculated on the assumption that the crust has a pure-ice composition and that there is an adiabatic temperature gradient in a liquid H_2O mantle and a core of hydrous silicates. I do not pretend that the temperature gradient in the mantle and core can be calculated to better than a factor of 2, but the only parameter changed substantially by allowing for these uncertainties is the central temperature, which can range from ~400° to ~800°K. All other important features of the model, including the thickness of the crust and the depth of the mantle, are unchanged.

The boundary condition for both models is an average surface temperature of $160/\sqrt{2}$°K. The factor $1/\sqrt{2}$ arises from the fact that the radiating surface of the satellite, $4\pi R^2$, is four times larger than the cross section, πR^2, irradiated by the sun: energy balance requires that

$$c\pi R^2 T_0^4 = 4\, c\pi R^2 \bar{T}^4$$

or

$$\bar{T} = T_0\,(1/\sqrt{2})$$

Here c is a constant $\simeq 1$, T_0 is the surface temperature in the subsolar region, and $\bar{T}$ is the mean or effective surface temperature averaged over the the entire satellite. The central conclusion from such thermal models must be that these massive satellites have thin icy crusts, constituting only a few percent of the overall mass, overlying an extensive convective mantle of ammoniacal liquid water and a core of hydrous silicates and iron oxides. It is tempting to compare the conditions in the interior of such an icy satellite with the conditions necessary for the production of the mineral assemblages observed in the carbonaceous chondrites. Whereas present-day bodies in the solar system with radii of less than 600 km cannot have central temperatures above the NH_3-H_2O eutectic point, it is possible that, in the early days of the solar system, much larger heat sources were available and much smaller bodies could have been extensively melted. In addition to the long-lived radionuclides, which by themselves contributed several times the present-day heat flux 4.5×10^9 years ago, there are the possible contributions from short-lived radionuclides, accretion energy, and dissipation of energy by tidal interactions. We therefore might look for evidence of differentiation on objects much smaller than the Galilean satellites, including satellites as well as asteroids near the outer edge of the belt. The temperature gradient in the crust of a large icy satellite is roughly 1°K km^{-1} at present, but may have been larger, by a factor of 10, 4.5×10^9 years ago, even in the absence of short-lived radionuclides and intense dissipation of energy by tidal interactions.

Certainly liquid objects with thin icy crusts would be extraordinarily sensitive to the effects of hypervelocity impacts or intense tidal forces, either of which could easily break the crust. Reiffenstein (*8*) has suggested, on dynamical grounds, that destruction of liquid satellites just within Roche's limit could give rise to Saturn's ring system. This suggestion has been severely criticized on the grounds that the present-day gray-body equilibrium temperatures of Saturn are far below the melting point of ice (*9*). However, the melting point of ice has no significance in a multicomponent system. In addition, the effects of internal heat sources are plainly of immense importance in determining the temperature profile and melting behavior within such an object.

The crust of any such satellite that is massive enough to have undergone differentiation ($R > 500$ km) will be largely made up of ices. Thus its reflectivity at radar wavelengths may be exceptionally low, and detection of the Galilean satellites by active radar astronomy should be very difficult. A possible exception is Io (J I).

A general discussion of the physics and chemistry of the satellites of the outer planets, with a consideration of atmospheric composition, will appear elsewhere (*10*).

JOHN S. LEWIS

Planetary Astronomy Laboratory, Department of Earth and Planetary Sciences and *Department of Chemistry, Massachusetts Institute of Technology, Cambridge 02139*

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Runoff of Deicing Salt: Effect on Irondequoit Bay, Rochester, New York

Abstract. *Salt used for deicing the streets near Rochester, New York, has increased the chloride concentration in Irondequoit Bay at least fivefold during the past two decades. During the winter of 1969–70 the quantity and salinity of the dense runoff that accumulated on the bottom of the bay was sufficient to prevent complete vertical mixing of the bay during the spring. Comparison with 1939 conditions indicates that the period of summer stratification has been prolonged a month by the density gradient imposed by the salt runoff.*

The use of salt for deicing has increased sharply during the past few decades. Both calcium and sodium chloride are used, but the latter in far greater proportion (*1, 2*). Prior to 1941, it was common practice to apply chloride-treated sand to hills, curves, and intersections (*3*). By the late 1940's the use of pure chloride became common in a few localities. In more recent years,