TEMPERATURES WITHIN COMET NUCLEI. S.W. Squyres, C.P. McKay, and R.T. Reynolds, NASA Ames Research Center, Moffett Field, CA 94035.

The temperature at and below the surface of a comet nucleus is one of the most important parameters that affects the comet's behavior. It is also important to the proposed investigation of comets by spacecraft. As part of its core mission set, the Solar System Exploration Committee has recommended that NASA place high priority on a comet rendezvous mission. One experiment under consideration for this mission is a penetrator to be implanted directly into the nucleus. Among other instruments, this would include temperature sensors that could acquire temperature measurements at a number of depths from the surface down to 1 m. A model of heat transport within comet nuclei is important for planning of such an experiment, both for engineering purposes and for investigation of the information about nucleus physical properties that can be gained from temperature measurements.

For any given model of a comet nucleus' composition and structure, the temperature at any depth and time may, in principle, be calculated from a solution of the heat conduction equation with the appropriate physical properties for the material and the appropriate boundary conditions. We assume the problem to be adequately represented by a plane-parallel geometry with heat conduction in one (vertical) dimension; this assumption requires an upper and a lower boundary condition for solution. The upper boundary condition is given by the energy balance equation at the surface:

$$\left(K\frac{\partial T}{\partial z}\right)_{z=0} - \epsilon\sigma T_o^4 + \left[\left(\frac{e^{-\tau} S_o}{4r^2} + F_s\right)(1-A) + F_r\right] - \alpha p_v L\left(\frac{M}{2\pi R T_o}\right)^{1/2} = 0, \quad (1)$$

where T is temperature, z is depth, K is thermal conductivity, T_o is surface temperature, ϵ is thermal emissivity, σ is the Stefan-Boltzmann constant, τ is the optical depth of the coma, S_o is the solar constant, r is the distance from the sun in A.U., F_s is the flux of indirect light scattered onto the nucleus by the coma, A is the albedo, F_r is the downward flux of thermal radiation emitted by the coma, α is the coefficient of sublimation of the surface material, p_v is its vapor pressure, M is its molecular weight, L is its latent heat of sublimation, and R is the gas constant. The first term on the left-hand side of Eq. (1) is the heat conducted to the surface from below, and the second is the heat radiated from the surface to space. The third term is the energy deposited at the surface by radiation from above, including direct sunlight attenuated by the coma, indirect sunlight scattered onto the nucleus by the coma, and thermal radiation from coma grains that have been heated by sunlight. The fourth term is the heat loss due to sublimation at the surface (we assume pure H_2O). The lower boundary condition is simply zero net heat flux around an orbit. The conductivity of a porous icy medium may be represented as a combination of the conductivities of an ice fraction and a pore fraction. An expression for the thermal conductivity of a two-phase medium composed of spheres of one phase (pores) distributed in a matrix of another (solid) is *(1)*:

$$K = \frac{K_p}{4}\left[(2-3\phi)\frac{K_s}{K_p} + 3\phi - 1 + \left(\left[(2-3\phi)\frac{K_s}{K_p} + 3\phi - 1\right]^2 + 8\frac{K_s}{K_p}\right)^{1/2}\right] \quad (2)$$

where K_s is the conductivity of the solid phase, K_p is the thermal conductivity of the pores, and ϕ is the porosity. For the solid phase we use the thermal conductivity of ice I multiplied by the *Hertz factor,* which gives the fractional area of each grain that is in direct contact with other grains. We take the thermal conductivity of a pore to be the sum of the radiative conductivity K_r and the vapor diffusion conductivity K_v. For H_2O and the pore sizes under consideration, vapor diffusion at cometary temperatures is by free-molecular (Knudsen) flow. Both K_v and K_r are strongly dependent on temperature, and vapor diffusion dominates heat transport in porous frosts at high cometary temperatures.

To calculate the scattering and thermal contributions from the coma onto the nucleus we have developed a simple optical model of the coma. The dust emanating from the comet nucleus is swept by the gas and attains velocities comparable to the gas speed. We use these velocities and the production rate appropriate for the comet's temperature to calculate the distribution of dust around the nucleus. For the temperatures attained by comet P/Kopff (a candidate for the comet rendezvous mission), an optically thin (single scattering) approximation is valid. We solve the radiative transfer equations to obtain expressions for the attenuation of sunlight, the scattering of sunlight onto the nucleus by the coma, and the heating of the nucleus by infrared radiation from coma grains. The net effect of the coma is to produce a slight cooling of the nucleus.

The thermal properties of a comet's nucleus depend strongly on its porosity, pore size, and Hertz factor. Porous frosts with large pores and low Hertz factors show the largest variations in conductivity with changing temperature, as they undergo the least direct grain-to-grain conduction and the most radiative conduction and vapor diffusion. Conductivity generally increases with increasing Hertz factor. This dependence is strongest for low temperatures and small pore sizes, both of which inhibit radiation and vapor diffusion. The depth to which the annual thermal wave propagates of course depends on the thermal diffusivity of the material. The shape of the thermal profile is found to depend strongly on the relationship between conductivity and temperature. If conductivity increases strongly with temperature (as for very porous frosts), the near-surface thermal gradient is significantly more shallow near perihelion and more steep at aphelion than when the dependence of conductivity on temperature is weak. The equilibrium temperature at depth is close to the average surface temperature around the orbit, and also depends on the relationship between thermal conductivity and temperature. When conductivity increases strongly with temperature, more heat is conducted into the comet at perihelion and less is conducted out at aphelion than when conductivity depends weakly on temperature, creating a higher equilibrium deep temperature. We find that several temperature measurements in the upper meter of a comet nucleus can substantially constrain the thermal diffusivity of the material. We have also investigated the dependence of temperatures on the albedo and thermal emissivity of the nucleus. Both are unknown, and this uncertainty produces considerable uncertainty in the temperatures that would be encountered by a penetrator. The range of possible temperatures is not severe enough to present significant problems for instrument design (the γ-ray spectrometer under consideration for the penetrator must operate at < 120 K). With a determination of the albedo of the nucleus from the imaging experiment, the surface temperature measurement will yield the thermal emissivity of the material. Thermal emissivity and diffusivity, combined with detailed information on penetrability and isotopic composition, have the potential to yield much information about the physical and chemical nature of a comet's nucleus.

REFERENCE

Parrott, J.E., and A.D. Stuckes, *Thermal Conductivity of Solids,* Pion Limited, London, 1975.