THERMAL GRADIENTS IN INTERPLANETARY DUST PARTICLES: THE EFFECT OF AN ENDO-
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The interior temperature distribution as a function of time was modeled for particles ranging from 10
to 60 microns in radius experiencing rapid heating. The incorporation of a phase which undergoes an
endothermic transition, for example the dehydration of a hydrated silicate, is shown to produce a
transient thermal gradient which can persist for several seconds in the largest of these particles. This
is comparable to the time spent within 100 K of the peak temperature for some micrometeorites
entering the Earth's atmosphere. In these particles temperature indications derived from bulk or
interior properties, such as the presence of low-temperature minerals, tracks, and volatile elements,
may not reflect the surface temperatures reached on atmospheric entry. Thus, temperature indicators
measured in the interior may not be used to infer entry velocities for these particles.

Models of the heating experienced by micrometeorites on atmospheric entry assume the temperature of
the particle is the same throughout. Szydlik and Flynn (1) have confirmed that, for reasonable values
of thermal conductivity, particles whose heat transfer is dominated by thermal conductivity reach thermal
equilibrium on time scales short compared to the entry heating pulse. However Bonny et al. (2) proposed
that the phase transition of an organic material might slow this thermal equilibration, and Rietmeijer (3)
suggested decomposition of FeS might play a similar role. The dehydration and decomposition of the
hydrated silicates is strongly endothermic, thus hydrated IDPs contain a phase with the required properties.
Indications of thermal gradients in polar micrometeorites (4) and interplanetary dust (5) demonstrate that a
thorough investigation of the effects of endothermic phase transitions in micrometeorites is required.

Simulation Procedure

In this simulation each particle is modeled as a sphere of radius 0.05xR_p (where R_p is the radius of the
particle) surrounded by 19 concentric shells each of thickness 0.05xR_p. Initially the entire particle is at 300 K
the approximate temperature of a dust particle in space at 1AU. The exterior surface of the outermost shell
is suddenly heated to T_surf. The heat flow through each shell in a time interval dt = 0.0025 sec is
calculated using the heat transfer equation:

\[ dQ = kA(T_2 - T_1)\frac{dt}{h} \]  \hspace{1cm} (Equation 1)

where \( k \) = thermal conductivity, \( T_2 - T_1 \) = temperature difference across the shell, \( A \) is the cross-sectional
area, and \( h \) is the shell thickness. The temperature of each shell is then calculated by allowing the heat
transferred from the adjacent shell to warm the interior shell, that is:

\[ T = T_{\text{initial}} + \frac{dQ}{mc} \]  \hspace{1cm} (Equation 2)

where \( m \) is the mass of the shell and \( c \) is the specific heat of the material. If this heating would cause the
temperature of the shell to rise through the phase transition temperature the temperature remains at the
phase transition temperature until a sufficient amount of heat has been transferred to accomplish the phase
transition in this shell. Then the temperature of the shell is allowed to rise again following Equation 2. The
simulation continues in 0.0025 sec increments until the interior reaches the surface temperature.

Results of the Simulations

Figure 1 shows the temperature as a function of depth below the surface and time for simulations of
particles having radii of 50 microns, 30 microns, and 10 microns. In all cases shown a thermal conductivity
of 0.000002 cal/g.cm.K, the value measured at 300^\circ C for lunar soil in a vacuum (6), and a heat capacity of
0.2 cal/gm, a value typical for ordinary chondrites (7), were used. The phase transition temperature was 900 K,
and the phase transition was assumed to require 600 cal/gm. This value is similar to literature values for
the dehydration and decomposition of hydrated silicates. For example, the dehydration and decomposition
of kaolinite [Al_2Si_2O_5(OH)_4] requires the input of about 300 cal/gm.

For the 50 micron diameter particle, 3.8 seconds elapsed after the surface was raised to 1000 K before a
point 25 microns below the surface exceeded the phase transition temperature of 900 K. In the absence of
this endothermic phase transition the point 25 microns below the surface exceeds 900 K in less than 0.8
seconds. Thus, endothermic phase transitions can significantly extend the duration of thermal gradients in
micrometeorites. For steep entry angles some large IDPs spend only a few seconds within 100 K of their
peak temperature (8), thus the thermal gradient produced by this endothermic phase transition can result in
the interior never approaching the surface temperature.

If the surface temperature is increased the rate of heat transfer increases, and the duration of the thermal
gradient decreases. For a surface temperature of 1200 K the point 25 microns below the surface of this 50
micron particle reaches 900 K in only 1.6 seconds (see Figure 1). As particle size decreases, the duration of the thermal gradient also decreases. For a surface temperature of 1000 K, Figure 1 shows that it takes 1.3 seconds for the 30 micron radius particle to reach the condition that only the inner half is below the phase transition temperature, and the 10 micron particle takes only 0.14 seconds to reach this condition.

Implications for Atmospheric Entry Heating

For the 50 micron radius particle whose surface is rapidly heated to 1000 K, 3.8 seconds after the application of the heat at the surface 25% of the interior volume remained at or below the phase transition temperature. If the heating were stopped at this time, then the outer 25 microns of the particle would contain the thermally altered phase while the inner 25 microns would contain the unaltered phase. In addition, solar flare tracks, which are annealed at about 900 K, would be preserved in the inner half of the particle but erased in the outer region, and volatile elements with low temperatures lower than the phase transition temperature would be retained in the interior.

Internal thermometers, including the presence of tracks, mineral phases stable only at low temperatures, and volatile elements, are used to infer the sources of IDPs (9, 10). The effect of an endothermic phase transition is to establish a significant transient thermal gradient which allows the interior of the particle to remain at a lower temperature than the surface. If bulk particle properties are used to infer surface temperature, and place limits on the entry velocity of the particle, an endothermic phase transition will result in the underestimation of the particle heating, thus underestimating the velocity limit. This does not cause a serious complication for the identification of cometary particles using the method described by Flynn (9) and Love and Brownlee (10) since the cometary particles are those heated above a certain minimum temperature. However, identification of cometary particles would be compromised in particles containing phases which undergo exothermic phase transitions.


Figure 1: Temperature versus distance below the surface for 10, 30, and 50 um particles heated suddenly to 1200 K (top row) or 1000 K (bottom row) containing a phase having an endothermic phase transition at 900 K. Figures show only the outer half of the particle. See text for thermal parameters.