THERMAL INERTIA OF A METALLIC REGOLITH: A SIMULANT SAMPLE EXPERIMENT.
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Introduction: Tholen M-type asteroids have been assumed to have metallic composition because they exhibit featureless visible wavelength spectra and moderate albedos, similar to iron. However, there exists more diversity than expected in this main belt population. Measurements of radar albedo [1], near-infrared spectra [2], and 3-μm spectra [3] have revealed that surfaces of many M-types are likely composed of silicates. Low thermal inertias and silicate emission features at mid-infrared wavelengths also point to silicates on many of these surfaces [4]. There are six M-types that appear to have higher thermal inertias: 796 Sarita, 497 Iva, 184 Dejopeja, 771 Libera, 125 Liberatrix, and 216 Kleopatra [5]. When all evidence is considered, Kleopatra appears to be metallic, but with a lower than expected thermal inertia and density, a solid block of iron is an unlikely analog for 216 Kleopatra [6].

Although much higher than that of other asteroids of comparable size, the thermal inertia of Kleopatra is still much lower the thermal inertia of solid metal iron. Its measured value of a few x100 $JK^{-1}m^{-2}s^{-.5}$ is much lower, as values for iron and iron-rich materials can be as high as 16700 $JK^{-1}m^{-2}s^{-.5}$and 12000 $JK^{-1}m^{-2}s^{-.5}$ [5,7]. Like particulate basalt, it is possible that particulate iron has a lower thermal inertia than solid iron. To test this, we created a sample of metallic regolith simulant and sent it to Analysis Tech Inc., an electronics reliability testing lab, for thermal conductivity measurements. These measurements are used to interpret thermal inertias determined for M-type asteroids.

Methods: The regolith simulant was created by grinding a bar of stainless steel against a ten-inch steel bastard file. The grains produced were collected, and density and grain size distribution were measured. To calculate the density, the mass of a similar sample of stainless steel shavings was taken and compared to the mass of the same volume of water. Analysis Tech Inc. used a Thermal Interface Material test (TIM) to measure thermal conductivity. Four tests were run with three different temperatures and pressures ranging from 323 K and 10 psi (0.69 bar) to 393 K and 160 psi (11 bar).

Results: The results are shown in Table 1. Because of the temperature dependence of thermal conductivity, it is important to calculate the surface temperature of Kleopatra in order to interpret the test results. Using a standard temperature model, we calculated the temperatures of Kleopatra at apoapse and periapse. The subsolar temperature is calculated from

$$T_{ss}=((1-A)*S_0/(r^2\eta\varepsilon\sigma))^{1/4}$$

where A is bolometric bond albedo, S_0 is the solar constant, r is distance from the sun, η is a beaming parameter, ε is emissivity, and σ is the Stephan-Boltzmann constant.

The temperature distribution across the body is calculated by multiplying the subsolar temperature by the fourth-root of the cosine of the solar incidence angle. Parts of the body not facing the sun or in shadow are assumed to have a temperature of zero. This method produced a range of temperatures during apoapse of 105 K to 198 K. During periapse, temperatures fall in a more narrow range between 249 K and 257 K [5].

These calculations show that the highest temperatures the surface of Kleopatra reaches are still more than 70 K lower than the lowest temperature at which thermal conductivity was measured. The lowest pressure, 10 psi, is still much greater than the pressure in space as well.

	Temperature (K)	Pressure (psi)	Thermal Conductivity ($Wm^{-1}K^{-1}$)
Test 1	323	10	0.253
Test 2	324	150	0.307
Test 3	393	160	0.358
Test 4	393	160	0.322

Table 1. Four measurements for thermal conductivity were made at varying temperatures and pressures. The first measurement is most applicable to this research.

Because of these conditions, we consider the coldest and lowest pressure to produce the most pertinent measurement for thermal conductivities of asteroids. The value produced is 0.253 $Wm^{-1}K^{-1}$. Using this as an upper bound and a density of 1600 kgm^{-3}, we calculate thermal inertia (sqrt[$k\rho c_p$]). The thermal inertia of the metallic regolith simulant (<450 $JK^{-1}m^{-2}s^{-.5}$) is much lower than the thermal inertia of stainless steel in bulk form (8066 $JK^{-1}m^{-2}s^{-.5}$).

Discussion: Although the thermal inertia of Kleopatra was said to be greater than x100 $JK^{-1}m^{-2}s^{-.5}$no exact value was ever specified. Clearly 450 $JK^{-1}m^{-2}s^{-.5}$ exceeds this value; however, it should be noted that this is an upper limit for many reasons.

First, contact resistances during TIM artificially inflated the value of thermal conductivity derived. Secondly, since lower temperatures and pressures decrease thermal conductivity, and these tests were all performed at higher temperatures and pressures, the thermal conductivitieson an asteroid are likely even lower. The amount of overestimation can be partially constrained by previous work, indicating the actual value may be near or below 0.02 $Wm^{-1}K^{-1}$ [8].

Assuming that steel and steel powder are reasonably analogous to iron mixtures and iron-bearing powders, we can extend our result. Since the thermal conductivity of the simulant sample is 0.1% that of solid stainless steel, thermal conductivity of an iron-bearing regolith should be around 0.1% of a solid iron-bearing metal (0.04 $Wm^{-1}K^{-1}$), producing a thermal inertia near 200 $JK^{-1}m^{-2}s^{-.5}$. Because this is more similar to the thermal inertia measured for Kleopatra and the regolith on a body is an approximation for its interior, this experiment supports the possibility of Kleopatra being a metallic asteroid.

It should be noted that the thermal conductivity conversion factor for silica solid to silica regolith is .0006 [7]. Using an initial thermal conductivity for iron bearing solid of 40 $Wm^{-1}K^{-1}$ and this same conversion factor, a thermal conductivity of 0.024 $Wm^{-1}K^{-1}$ is found for iron bearing regolith. Notice this value is very similar to the 0.04 $Wm^{-1}K^{-1}$ mentioned above. Although not the intension of this study, this implies that the physical process that causes the reduction of thermal conductivity may be the same for silicate and metal. It also suggests that thermal conductivity is more dependent on the geometric characteristics of grains than on composition.

Conclusion: Calculated values of thermal inertia of ground stainless steel are reasonably close to the thermal inertia measured for Kleopatra. This implies that metallic bodies, just like silica-rich bodies, experience gardening and regolith production. The differences in these processes induced by the variation in composition, however, are not understood.

Gardening, a churning process which smoothes regolith covered surfaces, is common on silica-rich asteroids and the moon. These bodies are bombarded with space debris, mixing materials from varying depths; however, on a metallic body, this process may be very different. The melting point of silica is higher than the melting point of iron, so more impacts may result in melting and beading of iron. This may also imply that the texture of the regolith itself is different on a metallic body.

The remaining question is perhaps the most fundamental. It has long been believed that these unique metallic bodies are the source of iron metal meteorites and the cores of ancient bodies torn apart. To be able to state more conclusively that Kleopatra is a stripped core and iron meteorite progenitor, a simulant should be made with a composition more similar to that of iron meteorites and thermal inertia for this powder calculated. Preferably, the thermal conductivity would be measured in a vacuum and in very low temperatures. To confirm the existence of a metallic regolith, a sample return from Kleopatra or another proposed M-type would be ideal. Future studies would greatly benefit our understanding of not only metallic regolith but on a larger scale, cores during early solar system formation.

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