AGUAS ZARCAS (CM2) LOW TEMPERATURE THERMOPHYSICAL PROPERTIES. C. P. Opeil,1,2 G. J. Consolmagno,1 D. T. Britt,1 and R. J. Macke1 1Vatican Observatory (V-00120, Vatican City State, brother_guy@me.com; macke@jesuits.net) 2Department of Physics, Boston College (Chestnut Hill, MA 02467, USA, opeil@bc.edu) 3Center for Lunar and Asteroid Surface Science, and Department of Physics, University of Central Florida (Orlando, FL 32816, USA, dbritt@ucf.edu).

Introduction: Aguas Zarcas (AZ) is a brecciated carbonaceous chondrite (CM2) containing both chondrule-poor and chondrule-rich lithologies [1]. The AZ samples collected immediately after the fall (on 23 April 2019 in Aguas Zarcas, Costa Rica) provide a rare opportunity to analyze the mineralogy of a CM2 largely free of terrestrial contamination [2,3,4]. We report low-temperature specific heat capacity, thermal conductivity, and linear thermal expansion data over the range 5 ≤ T ≤ 300 K. From these data, we calculate thermal inertia and thermal diffusivity as a function of temperature. Measurements follow the procedures as described in [5] utilizing a Quantum Design Physical Property Measurement System (QD-PPMS) at Boston College. Our primary reason for presenting these results are the petrological comparisons noted [1, 3,6,7,8] between AZ and samples returned from the asteroid 101955 Bennu by the OSIRIS-REx mission.

Specific Heat Capacity: Specific heat capacity (c_p) is an intrinsic material property signifying the amount of heat energy necessary to raise the temperature of a certain mass of a material. Measurements of specific heat capacity (c_p vs. T) of AZ are shown in Fig. 1 (right vertical axis, open circles). Data are independent of meteorite porosity and structure. The temperature dependence is very pronounced, particularly at temperatures below < 100 K. The specific heat capacity for the specimen in this study varies by a factor of 55.6 between 5 and 100 K, and by a factor of 2.7 from 100 to 300 K. These heat capacity data confirm the strong low-temperature dependence at T ≤100 K and indicate the high-temperature saturation behavior at T > 250 K.

Thermal Conductivity: Data for thermal conductivity (κ vs. T) are shown in Fig. 1 (left vertical axis, filled squares). Unlike specific heat capacity, the value of κ is directly linked to sample porosity, cracking and disorder. The curve decreases monotonically with temperature as expected in a conglomerate material with crystalline disorder; no sharp peaks or evidence of phase transitions are indicated. At 300 K we note that κ ~ 0.3 W m⁻¹ K⁻¹ has a lower value than other CM2 carbonaceous chondrites [5]. Furthermore, κ changes by a factor of 1.6 from 100-300 K and changes by a factor of 6.3 from 5-100 K. Overall, this κ is much lower than that of the sample’s individual component minerals, indicating the importance of porosity, voids, cracking, and sample disorder which inhibit heat flow.

Thermal Inertia: Data for thermal inertia (Γ vs. T) are shown in Fig. 2 (left vertical axis, open triangles). Because Γ varies as the square root of the product of heat capacity and thermal conductivity, it is a very strong function of temperature over the entire thermal range in this study (Γ = ρ/2² c_p/1/2 κ/1/2) [9]. It increases by a factor of 18.7 from 5 K to 100 K, and by another factor of 2.1 from 100 K to 300 K. At extremely low temperatures, where both conductivity and heat capacity tend toward zero, Γ likewise trends continuously toward zero as it approaches 0 K; here it is much more well-behaved function of temperature than thermal diffusivity.

Thermal Diffusivity: Thermal diffusivity (Dr) vs. T values are calculated as (Dr = κ / ρ c_p) from density, ρ, c_p, and κ. Data are shown in Fig. 2 (left vertical axis, filled triangles).

Thermal diffusivity has units of area per unit time and measures how quickly a material transports heat or how quickly a material’s temperature can rise. Because thermal inertia and thermal diffusivity are both calculated from heat capacity and thermal conductivity (and density, assumed here to be independent of temperature), both of these properties likewise are strong functions of temperature. In the case of thermal diffusivity, which varies with the ratio of these factors, the temperature dependence flattens out above 50 K. From 50 to 300 K, Dr changes by a factor of 2.5. Below 50 K, however, thermal conductivity and heat capacity ex-
hbit vastly different behaviors with temperature: the denominator (heat capacity) trends towards zero faster than thermal conductivity. Thus as temperature drops the thermal diffusivity can increase to a maximum, before falling toward zero at absolute zero. From 5-50 K, Dr changes by a factor of 5.7.

Figure 2: Calculated thermal inertia vs. T (right, unfilled inverted triangles) and thermal diffusivity vs. T (left, filled triangles).

Linear Thermal Expansion: Thermal expansion is the tendency of matter to change its shape in response to a change in temperature. As temperature increases, the average atomic kinetic energy of a material rises and the object tends to expand ($\Delta L = \alpha L_0 \Delta T$). We used a capacitive dilatometer to measure the thermal expansion of AZ to determine the linear thermal expansion coefficient ($\alpha_L$) over the temperature range of 5 to 300 K. In the rare case that materials contract rather than expand with increasing temperature, they are said to experience negative thermal expansion (NTE).

Fig. 3 shows how $\alpha_L$ varies with T for AZ. Note the significant NTE; this is likely due to the layered structure of the phyllosilicates that dominate the AZ mineralogy [5]. The “oxygen-cation-oxygen” molecules that connect the phyllosilicate layers vibrate in both longitudinal and transverse directions. The transverse vibrations are temperature dependent and cause a contraction (from 200 to 240 K) between the phyllosilicate layers. If the entire meteorite/asteroid heats and cools uniformly, the effect of this NTE is negligible; however, if a meteorite/asteroid does not heat uniformly then stress fractures can appear in the material. Over time, fractures on asteroidal surfaces containing CM2-like material can lead to rubble pile formation [10,11,12].

Figure 3: Coefficient of thermal expansion vs. T (filled circles). Negative thermal expansion (NTE) onset at $T \sim 200$ K, temperature of maximum rate of NTE at $T \sim 230$ K, positive thermal expansion recovery appears at $T \sim 245$ K.

Implications for Aguas Zarcas and Bennu: From the initial investigations of the Bennu sample density, thermal inertia, IR spectroscopy and lithology [1,6,11,12] there seem to be notable similarities with the carbonaceous chondrite (CM2) AZ. Upcoming investigations of the thermal and physical properties of the Bennu samples may reveal further similarities with CM1/2 meteorites, along with a few surprises.

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