LOW-TEMPERATURE SPECIFIC HEAT CAPACITY AND LINEAR THERMAL EXPANSION OF MATERIAL FROM ASTEROID 101955 BENNU. C. P. Opeil[1], J. Biele[2], J. L. Smith[3], A. J. Ryan[4], J. L. Molaro[4], R.-L. Ballouz[5], R. J. Macke[6], H. C. Connolly, Jr.[4,7,8], D. S. Lauretta[4]. [1]Department of Physics, Boston College, Chestnut Hill, MA, USA (opeil@bc.edu), [2]German Aerospace Center (DLR), Köln, Germany, [3]Los Alamos National Laboratory, Los Alamos, NM, USA, [4]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [5]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [6]Vatican Observatory, Vatican City State, [7]Department of Geology, Rowan University, Glassboro, NJ, USA, [8]Department of Earth and Planetary Sciences, American Museum of Natural History, New York, NY, USA.

Introduction: OSIRIS-REx returned a sample from asteroid (101955) Bennu on 24 September 2023. Bennu was chosen as the target of study because of its primitive origins dating to the birth of our Solar System [1]. Bennu has a low-albedo surface and is classified as a B-type (spectrally blue) asteroid, a sub-type of the carbonaceous (C-type) asteroids. Low-temperature measurement of specific heat capacity (3–250 K), a key parameter in determining thermal inertia, allows a thermodynamic profile of this asteroid material for comparison with CM and CI meteorites and other asteroids, helping us to understand the chemical evolution of the early solar system. Thermal expansion measurements (12–300 K) provide data for thermal fatigue modeling and understanding the evolution of asteroid surface material [2, 3]. Such measurements inform the primary hypothesis of the OSIRIS-REx mission of how the surface materials of Bennu have been modified by exposure to space.

Sample: The Bennu sample used in these measurements (OREX-800107-104, 31.9 mg) was a subset of a homogenized powder of aggregate (loose, unsorted) material [4]. The sample was pressed into a cylindrical pellet 3.0 mm in diameter with a calculated volumetric bulk density of 2.561 g/cm^3. The pellet was heated to 130 Celsius for 30 minutes to remove any absorbed water from the atmosphere and immediately placed into He cryostat.

Specific Heat Capacity: Measurements of specific heat capacity vs. temperature (T) of Bennu are shown in Fig. 1 [5]. The low-temperature measurements were made using a Quantum Design Physical Property Measurement System (QD-PPMS) at Boston College. The QD-PPMS He cryostat uses a hybrid adiabatic relaxation heat capacity method [6, 7]. The thermodynamic data are independent of porosity, density, 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 89.5 between 3 and 50 K, by a factor of 3.0 from 50 to 100 K, by a factor of 1.6 from 100 to 150 K, by a factor of 1.3 from 150 to 200 K, and by a factor of 1.2 from 200 to 250 K. These heat capacity data confirm the strong low-temperature dependence and indicate the high-temperature saturation behavior at $T > 250$ K. Previous low-temperature specific heat capacity measurements on CM carbonaceous chondrites show comparable data [7].

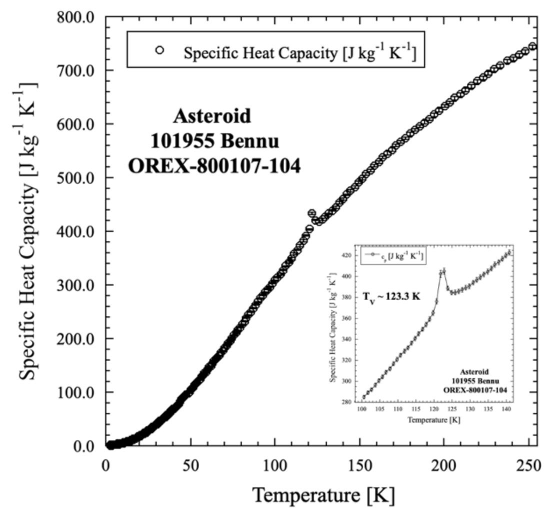

Figure 1: Specific heat capacity vs. T for the Bennu pressed pellet sample (OREX-800107-0). Inset: Close up of the Verwey transition, $T_V \sim 123.3$ K.

Verwey Transition: A Verwey transition is a low-temperature phase transition in the naturally occurring mineral magnetite (Fe_3O_4) near $T_V \sim 125$ K. The monotonic specific heat capacity vs. T curve of Bennu is offset by a first order, lambda transition as indicated in Fig. 1 at $T \sim 123.3$ K; a detailed view is shown in the inset. The presence of magnetite on Bennu and this transition was predicted by measuring the spectral absorption at 0.55 μm of the Bennu surface [8, 9, 10]. This transition is associated with significant changes in the magnetic, electrical, and thermal properties [11, 12, 13]. Magnetite is a relevant mineral component of carbonaceous chondrites and samples returned from C-type asteroid (162173) Ryugu [9]. The presence of magnetite is an important indicator of the past aqueous alteration of its host body [14].

Linear Thermal Expansion: As temperature increases, the average atomic kinetic energy of a material rises and materials tend to expand. The linear thermal expansion coefficient, α, is given by the equation $\alpha = \Delta L \ \Delta T^{-1} \ L_o^{-1}$, where L_o is the original sample length, ΔL is the change in length, and ΔT is the change in temperature. A capacitive dilatometer was used in conjunction with a QD-PPMS cryogenic refrigerator to determine α over the temperature range of 12 to 300 K. The sample was the same compressed pellet (height = 1.761 mm) utilized for specific heat capacity measurements. In the rare case that materials contract rather than expand with increasing temperature, they experience negative thermal expansion (NTE). Such NTE is indicated by a negative slope in the curve of α vs. *T*. A positive thermal expansion (PTE) is indicated by a positive slope in the thermal expansion curve.

Fig. 2 shows how α varies with *T* for the Bennu sample. Note the significant NTE; this is likely due to the layered structure of the phyllosilicates that dominate the Bennu mineralogy [8]. Previous studies of CM2 carbonaceous chondrite meteorite samples [7, 15] show similar NTE behavior over the same *T* range.

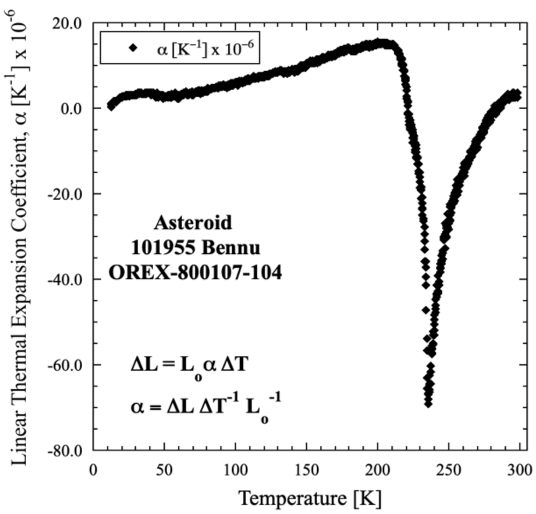

Figure 2: The linear thermal coefficient of expansion vs. *T* is shown. A sharp onset of negative thermal expansion (NTE) occurs at *T* ~ 200-240 K. At higher *T* a positive thermal expansion (PTE) appears.

The primary difference between the Bennu and CM2 data [7] is the depth of the transition. The linear thermal coefficient of expansion, α, of Bennu changes by 8.5×10^{-5} [K^{-1}] where the largest change observed in the meteorite Jbilet Winselwan [7] is 2.4×10^{-5} [K^{-1}]. This difference, a ratio of 3.5, is attributed to the pristine nature of the Bennu sample in contrast to the weathering and other environmental effects on the meteorite sample. Future linear thermal expansion measurements on CI meteorites are likely to show strong NTE behaviors similar to those found in the Bennu sample.

The mechanism of the NTE lies in the oxygen-cation-oxygen molecules that connect the phyllosilicate layers and 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 [7]. If the entire asteroid heats and cools uniformly, the overall effect of this NTE could be negligible. However, this is not the case due to the non-infinite thermal inertia of the surface materials. Near-surface diurnal thermal gradients can lead to the development of stress fractures in the material. Over time, thermal fracturing rates can influence how the surfaces of different bodies evolve. Thus, on Bennu, because of the predominance of phyllosilicates in the boulders, as well as the surface temperature cycling between 200–350 K, we should expect comminution of boulders into regolith [16, 8 , 2, 17, 18].

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