LINEAR THERMAL EXPANSION OF CM2 CARBONACEOUS CHONDRITES

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Abstract: Measurements of the low-temperature thermodynamic and physical properties of meteorites provide fundamental data for the study and understanding of asteroids and other small bodies. Such studies are designed to characterize fundamental processes that occur both within the heliosphere and throughout the universe. [1] Of particular interest are the CM carbonaceous chondrites, which represent a class of primitive meteorites that record substantial chemical information concerning the evolution of volatile-rich materials in the early solar system. CM chondrites contain anhydrous minerals such as olivine and pyroxene, along with abundant hydroxyl phyllosilicates contained in the meteorite matrix interspersed between the chondrules. We have measured the thermal expansion of five CM carbonaceous chondrites (Murchison, Murray, Cold Bokkeveld, Northwest Africa 7509, Jbilet Winselwan) from 5-300 K, which spans the range of possible surface temperatures in the asteroid belt and outer solar system. The thermal expansion measurements show a substantial and unexpected decrease in CM volume as temperature increases from 210 - 240 K followed by a rapid increase in CM volume as temperature rises from 240 - 300 K. Similar transitions are absent in anhydrous CV or CO carbonaceous chondrites, lunar or martian meteorites measured under similar conditions. We believe these are the first negative thermal expansion (NTE) meteorite data reported in the literature. [2] In order to confirm this NTE in the CM2 meteorites, we performed heat capacity measurements at small temperature intervals from 190-280 K. When taking the derivative of the heat capacity with respect to temperature ($d\epsilon /dT$ vs. $T$), we observe a decrease in $d\epsilon /dT$ at the same temperatures as those shown in the linear thermal expansion. The heat capacity results confirm the thermodynamic change seen in the NTE behavior.

(1) Introduction:

(a) Heat capacity, thermal conductivity, thermal diffusivity, density, porosity and thermal expansion are the fundamental thermodynamic and physical meteoritic characteristics for modeling various aspects of the orbital and internal evolution of asteroids and small solar system bodies. These characterization techniques help to identify material and composition dynamics in the meteorite itself.

(b) Negative thermal expansion is a rare phenomenon. Most terrestrial and extra terrestrial materials expand/contract in a smooth, uniform fashion unless there is a structural or magnetic transition as a function of temperature. High porosity and low bulk density of CM2 meteorites make them poor candidates for structural or magnetic transitions. Yet, measurements indicate for this classification of meteorites (CM2) a robust and repeatable NTE transition exists.

(c) CM2 meteorites consist largely of tetragonal and octahedral sheets of phyllosilicate material (clay) connected by hydroxyl (OH) groups. These hydroxyl groups can vibrate with longitudinal and transverse vibrations. [5, 6] These characterization techniques help to identify material and composition dynamics in the meteorite itself.

(d) CM2 meteorites contain phyllosilicates, naturally occurring phyllosilicates arranged in tetrahedral and octahedral layers. The phyllosilicates are temperature dependent. [3] Specific heat capacity (c\textsubscript{p}) vs. T measurements indicate NTE across a broad T range which occur for different samples at approximately the same temperature $\approx$ 235 K. Measurements shown were taken at a cooling rate of 0.25 K/min on a capacitive dilatometer with a resolution of $\approx$ 0.8 Angstrom. Error bars are included and are smaller than the symbols.

(2) Linear Thermal Expansion vs. T (5-300 K)

Fig. 1: Linear thermal expansion (\text{\textit{a}}) vs. T measurements indicate NTE across a broad T range which occur for different samples at approximately the same temperature $\approx$ 235 K. Measurements shown were taken at a cooling rate of 0.25 K/min on a capacitive dilatometer with a resolution of $\approx$ 0.8 Angstrom. Error bars are included and are smaller than the symbols.

(3) Specific Heat Capacity vs. T (2-300 K)

Fig. 2: Specific heat capacity (c\textsubscript{p}) was measured using a thermal relaxation technique for $\approx$ 20 mg samples with approximate dimensions of $\approx$ 1 x 3 x 3 mm. The data are offset on the vertical axis by multiples of $\approx$ 175 J/Kg-K for clarity. Lines are added as a guide to the eye. Error bars are present but smaller than the data symbols.

(4) Specific Heat Capacity vs. T (190-280 K)

Fig. 3: Specific heat capacity (c\textsubscript{p}) vs. T open symbols) are plotted along with $d\epsilon /dT$ vs. T (solid symbols) in the temperature range 190-280 K. The data for both c\textsubscript{p} and $d\epsilon /dT$ are offset in the vertical scale for clarity. The c\textsubscript{p} vs. T data reveal in its derivative $d\epsilon /dT$ a broad thermodynamic transition in a temperature region consistent with changes in linear thermal expansion.

(5) Longitudinal and Transverse Mode Vibrations:

Fig. 4: Longitudinal and transverse vibrational modes of the cation, anion and OH groups are temperature dependent. Transverse vibrations (right hand side) allow $\theta < 180^\circ$ and are responsible for the NTE as transverse mode vibrations dominate longitudinal vibrations. [5, 6]

(6) Conclusions/Analysis:

(a) The unusual NTE behavior observed at $\approx$ 235 K, as shown in Fig. 1, is likely due to the temperature dependent contraction of the layered structure of hydroxyl phyllosilicates that dominate the mineralogy of the CM2 meteorites. The dynamic interaction of the longitudinal and transverse vibrational components between the tetrahedral and octahedral layers produces this NTE as a function of temperature.

(b) Normally, all materials at a transition show abrupt changes in both the $c\textsubscript{p}$ and $d\epsilon /dT$ as a function of T according to the Ehrenfest relation. We argue the high bulk porosity and low density of CM2 meteorites mask a large bulk thermodynamic change which can only be observed in the behavior of $d\epsilon /dT$ vs. $T$.

(c) This behavior seems particular to CM2 meteorites and it is likely that parent bodies of CM2 material would be prone to cracking if they experience repeated temperature changes between 200-300 K. This is a reasonable assumption due to the non-uniform solar heating/cooling patterns in space.

References:


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