ORDINARY CHONDRITE HEAT CAPACITIES BELOW 350K. R. J. Macke,[1] C. P. Opeil[2], G. J. Consolmagno[1], and D. T. Britt[3,4] [1]Vatican Observatory, V-00120 Vatican City State, rmacke@specola.va; [2]Boston College Department of Physics, 140 Comonwealth Ave., Chestnut Hill MA 02467, cyril.opeil@bc.edu; [3]University of Central Florida Department of Physics, 4111 Libra Dr, Orlando FL 32816, britt@physics.ucf.edu; [4]Center of Lunar and Asteroid Surface Science, 12354 Research Pkwy Suite 214, Orlando FL 32826.

Introduction: *Thermal diffusivity*, which determines the thermal evolution of asteroid interiors, and *thermal inertia*, which at the asteroid surface determines the various Yarkovsky effects, are both dependent on heat capacity (C_p), thermal conductivity (κ), and bulk density (ρ). We have been conducting a study of these thermal properties over the temperature range 5-350K for various types of meteorites using samples from the Vatican collection. Here we present our low-temperature heat capacities for ordinary chondrites.

Method: We use three techniques to determine low-temperature heat capacities of ordinary chondrites. To establish the shape of the temperature-depedent curve, we measured heat capacities for small (~5 mm^3) samples using a Quantum Design Physical Property Measurement System (PPMS) with a P-650 package [cf. 1]. This technique could only be applied on a limited number of samples, so to extend the breadth of data we measured several hand-sized samples from the Vatican Observatory using a non-destructive liquid nitrogen (LN2) immersion technique [2]. This technique provides the average heat capacity over a range from 77-294K, which yields a good estimate of C_p at 175K. We measured 6 ordinary chondrites using the PPMS, and 72 ordinary chondrites using the liquid nitrogen immersion technique.

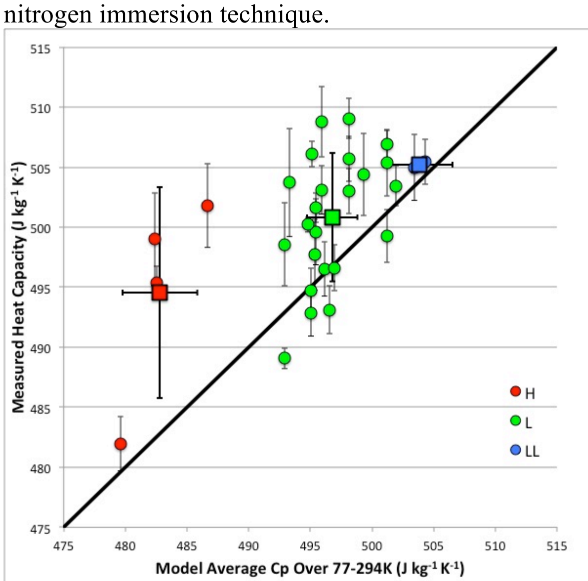

Fig. 1: C_p measured by LN2 immersion vs. model C_p at 175 K for OC falls. Circles are individual stones. Squares represent averages.

Finally, in addition to laboratory data, for several ordinary chondrite falls for which compositional data had been published in [3], we constructed model heat capacities as a function of temperature based on the heat capacity curves for each of the component minerals, weighted by their fractional mass. Of these, we also have 175K C_p measurements for 29 of the same meteorites from the Vatican collection.

Results and Analysis: Fig. 1. compares our 175K LN2-immersion results for the Vatican samples with composition-based model heat capacities for the same OC falls. The LN2 and model results are fairly good agreement to within about 3% for all samples. The observed discrepancies may be due to inhomogeneity at cm scales between individual stones of the same meteorite and low-level sample weathering may play a role in the observed discrepancies. Note that composition models assume all metallic iron is intact and unweathered, while minor terrestrial weathering inevitable affects even fall samples. Since the weathering product has a higher C_p than metallic iron, weathering would result in increased C_p. All of our discrepancies can easily be accounted for by assuming just a few percent of metallic iron has been weathered. The greatest discrepancies are for H chondrites, which have the greatest amount of metallic iron to weather. In general, finds also have a higher C_p than falls of the same type. This again is the result of terrestrial weathering on metallic iron, and also generally corresponds to a reduction in grain density characteristic of weathering.

175-K heat capacities for OC falls lie within a limited range of 481 to 524 J kg^{-1} K^{-1}, comparable to other stony meteorites [Fig. 2] and significantly higher than that of unweathered irons and mesosiderites. H, L, and LL heat capacities each occupy compact yet overlapping ranges, with H having the lowest C_p of the three and LL the highest. The differences between the three groups are almost entirely based in the difference in metallic iron content.

C_p as a function of temperature: We measured $C_p(T)$ over the range 5-350 K for 6 individual specimens using the Quantum Design PPMS system. From these data, we fit a curve of the form $C_p(T) = a+bT+cT^{-2}+dT^{-1/2}$ for each meteorite over the temperature range 75-300K. We then computed the coeffecients of the curve for each of the composition mod-

els based on [3] and the coefficients for average-composition H, L, and LL falls [Table 1]

We were also able to compare laboratory results with the average composition models. Several falls compared very well with the average of their type [Fig. 3]. However, the 19th century fall Oesel and the dry desert find Jiddat al Harasis (JAH) 073, did not compare as well. All discrepancies were toward slightly higher C_p in the laboratory data than in the models, indicative of weathering.

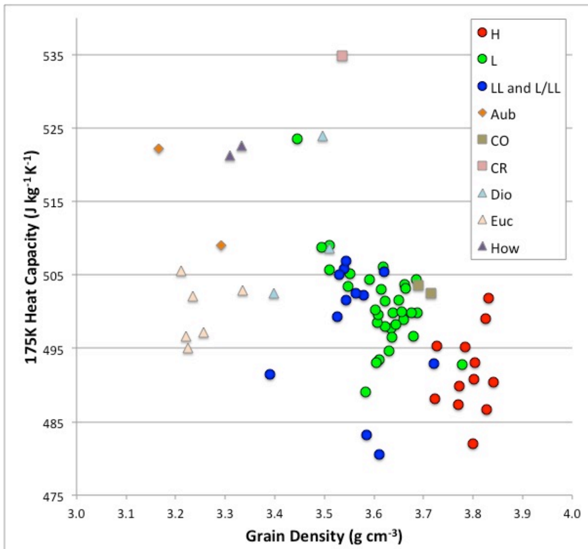

Fig. 2: Heat capacity vs. grain density for stony meteorite falls.

Discussion and Conclusion: This study provides an important step in the overall goal of describing meteorite thermal properties for the purpose of modeling the thermal behavior of asteroids. Unlike thermal conductivity, heat capacity is independent of structural considerations like porosity; this study confirms that modeling heat capacity based on composition does yield reliable results. Our next step will be to model these meteorites at higher temperatures (>350K) to aid future modeling of meteorite C_p for other meteorite types and at temperatures outside the range of what can be measured with our existing equipment.

If the discrepancies between model heat capacities and laboratory data are due to the weathering of metallic iron in the meteorite, this suggests that one might use the amount of this discrepancy to quantitavely determine degree of weathering of iron metal. We hope to confirm this by comparing our results for the degree of weathering with more established techniques such as Mössbauer spectroscopy.

However, our ultimate goal is to determine meteorite parent body thermal inertia and thermal diffusivity. The heat capacity data reported here and our extensive database of meteorite density and porosity [4] provide the first two necessary elements. We are currently gathering data for thermal conductivity, which is dependent on porosity and structure, and are exploring how these data vary with structural conditions.

References: [1] Opeil C. P. et al. (2012) *Meteoritics & Planet. Sci.* 47, 319-329. [2] Consolmagno G. J. et al. (2013) *Planet. Space Sci.* 87, 146-156. [3] McSween H. Y. et al. (1991) *Icarus* 90, 107-116. [4] Macke R. J. (2010) Ph.D. dissertation, Univ. Cent. Fla.

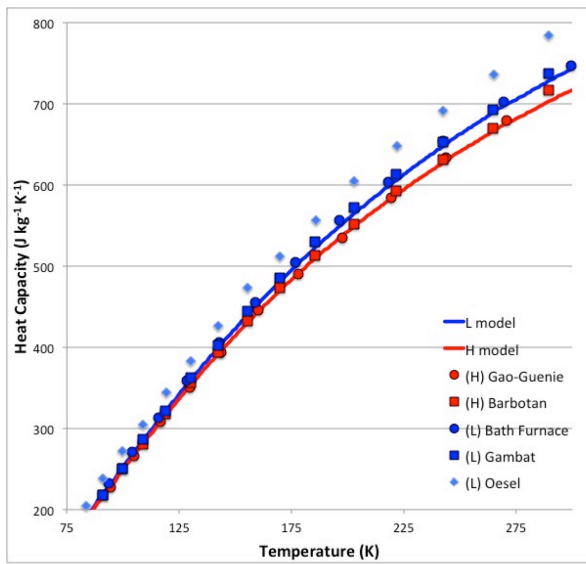

Fig. 3: Heat capacity vs temperature for several meteorites. The solid red and blue lines represent H and L average models based on [3]. The dots are PPMS-based laboratory data. In general, models and laboratory data agree well.

Table 1: Coefficients for $Cp(T) = a + bT + cT^{-2} + dT^{-1/2}$ using composition models

Type	C_p(175K) [J kg^{-1} K^{-1}]	a	b	c	d
H average	482.9	1375.1	0.28159	1.5691 $x10^6$	-1.3124 $x10^4$
L average	496.3	1410.6	0.34728	1.7046 $x10^6$	-1.3645 $x10^4$
LL average	501.4	1434.5	0.36192	1.7880 $x10^6$	-1.3971 $x10^4$