SCALE DEPENDENCE IN POROSITY FOR INTACT STONES OF KOŠICE

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Introduction: On February 28, 2010, a fireball was observed over eastern Slovakia. Through a series of expeditions between March and October of that year, 78 specimens of the H5 chondrite Košice were recovered for scientific study at Comenius University and the Astronomical Institute of SAS, ranging in mass from 0.56 g to 2.37 kg [1]. The major part of these specimens were intact, fully fusion-crusted stones. The physical properties of 67 intact specimens were measured by Kohout et al. [2], who observed that variability in porosity grows with small specimen sizes, and that porosity is suppressed in larger specimens. That study, however, used the Archimedean bead method for measuring bulk density (a necessary step in determining porosity). The bead method lacks the precision necessary for making fine distinctions between objects of similar density, in particular for very small specimens < 10 g (< 3 cm^3), and so it was not possible with those data to study scale dependence in porosity to any detail.

With the development of the reliable high-precision laser scanning techniques for measuring bulk density [cf. 3], it became possible to study scale-dependent trends in bulk density and porosity for very small specimens, even below 1 cm^3. The laser scanner at the Vatican Observatory was brought to Comenius University, where it was applied to 32 specimens ranging from 0.66 g to 2.37 kg. Almost all of these were fully intact and fully fusion crusted. A few had lost a part of the fusion crust but were otherwise fully intact, and one > 100 g specimen had had a small chip removed for analysis but was still representative of a specimen of its size.

Measurement: For 28 of the 32 specimens, grain density data existed from previous studies [2]. Grain densities were determined by ideal gas pycnometry using a Quantachrome Ultrapyc 1200e. Bulk densities for all specimens were determined by a NextEngine model 2020i laser scanner with the HD Pro upgrade. The scanner produced computer shape models of the meteorites, from which volumes were calculated. The precision of the laser scanner allowed for bulk density determinations better than 0.03 g cm^{-3} (better than 1%) for all specimens greater than 3 g, and usable results for even the smallest specimen. Of these, 13 had not been previously measured in [2]. (11 were too small for reliable results from the bead method, and 2 were too large to fit in the measurement apparatus.) Porosities were determined from grain (ρ_g) and bulk (ρ_b) densities: $P = 1 - (\rho_b / \rho_g)$.

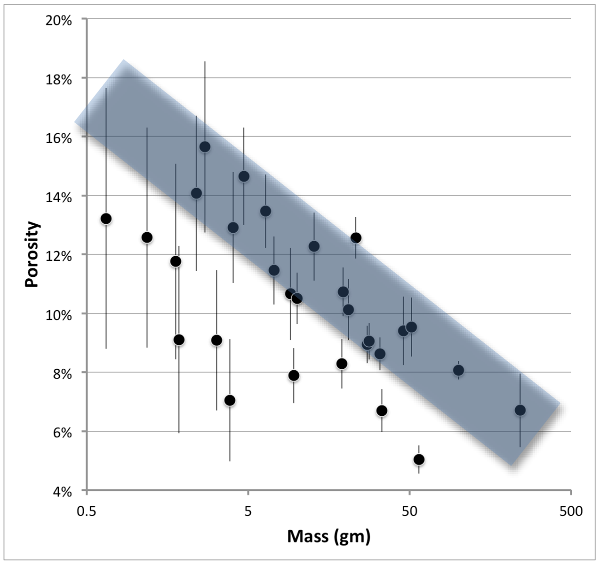

Figure 1: Porosity as a function of mass for specimens in this survey. The mass axis is logarithmic. Computed model porosities are not included in this figure. Note the negative trend between porosity and mass, nearly linear in log(mass) except for ten outliers at lower porosity.

Results and Analysis: Porosities ranged from 5% to 16%, with the most porous specimens all being less than 7 g. The three largest specimens in this study (208.8 g, 241.2 g, and 2367 g)—as well as one intermediate sized specimen—lacked grain densities. The largest specimen among those with complete data (100.2 g) was 8% porous. For the three largest, we estimated grain densities based on the grain densities of specimens of similar size, using the more complete data set from [2], and used these to compute model porosities. All three have model porosities in the range 6-8%, with the largest being 7% porous.

While porosity varies greatly at all masses, the maximum porosity for all but the largest specimens follows a definite negative slope as a function of mass [Fig. 1]. As the Košice-producing meteoroid experienced stresses upon entry in Earth's atmosphere and broke apart, the size of the individual stones that remained intact would have been dependent on the strength of the material comprising different portions of the object. Weaker material would have broken into

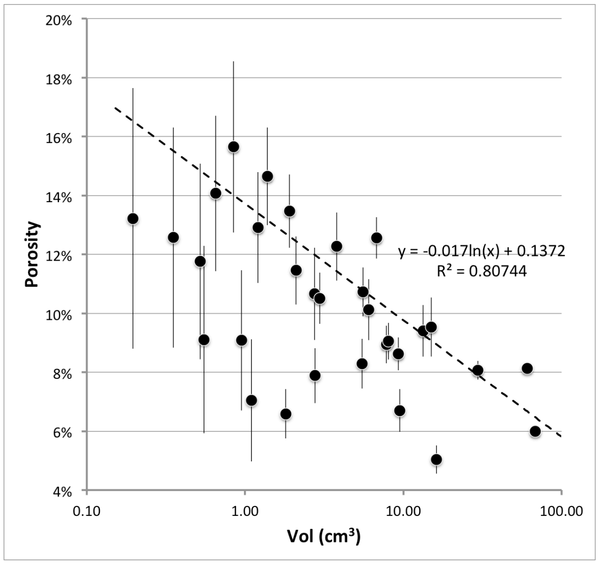

Figure 2: Porosity as a function of bulk volume. The volume axis is logarithmic. In this plot, model porosities for three additional specimens less than 250 g are included. The dashed line represents a fit to all data except the 11 outliers that have significantly lower porosities than their neighbors.

smaller fragments. Since porosity compromises strength, it would make sense that the more porous material would have broken into smaller fragments.

It is interesting to note that Košice, being a fairly normal and homogeneous example of an H5 chondrite, clearly exhibits scale-dependent variation in porosity that cannot be accounted for by measurement effects and uncertainty. Most of the specimens align not far from the porosity-mass curve marking the upper boundary of the population. Only 10 of 28 lie significantly below the maximum. Some of these exhibit signs of terrestrial weathering, which lowers porosity [4]. Others may have experienced localized stresses that resulted in them breaking into smaller pieces.

One can attempt to quantify the porosity-size relationship. From [5], compressive strength is a function of specimen volume: $\sigma = [C_1]\ V^m$, where m and $[C_1]$ are material-dependent parameter. A source dealing with strength of concrete [6]—structurally similar to chondritic material—relates compressive strength to the exponential of the porosity: $\sigma = [C_2]\ e^{-nP}$, where n is a material-dependent parameter and $[C_2]$ is a function of Young's modulus and fracture energy at zero porosity, and the average crack size. Combining the two yields a relation between porosity and volume of the form:

$P = -A \ln V + B$,

where A is the ratio of the material-dependent parameters m and n, and B is a function of $[C_1]$ and $[C_2]$.

Plotting porosity against specimen volume [Fig. 2] (this time including model porosities) again reveals a negative logarithmic relation between the porosity and the volume for the specimens marking the highest porosities in their volumetric group. Omitting the 11 outliers (the ten from before plus one model porosity) allows for a pretty good logarithmic fit of the form:

$P = -0.017 \ln V + 0.137$.

This fit is limited, however, to volumes less than about 100 cm^3. Beyond that, the porosity appears to be scale independent, leveling out at approx. 6-8 %. As mentioned before, the largest 2.37 kg specimen (679 cm^3) has a porosity of about 7%. Nevertheless, we cannot draw conclusions one way or the other for very large (multiple kg) specimens from these data.

Discussion and Conclusion: This study, illustrating the scale dependence of physical parameters such as porosity, demonstrates the importance of considering scale in future studies. It also illustrates the importance of developing high-precision measurement techniques. The results of this study could not have been obtained without the advent of high-precision laser scanning techniques. This study also demonstrates the importance of keeping a portion of the recovered meteorites from a strewn field intact. The study would not have been possible if the specimens had been fragmented, sliced, and otherwise processed for other studies.

To date, almost all studies of meteorite porosity have assumed that meteorites are generally homogeneous and that a sufficiently sized specimen is representative of the overall rock from which they originated. Almost no consideration has been given in porosity studies to the size of the intact stone; only to the mass of the fragment under study, often just a fraction of the size of the original stone. We see here that there is a size-based selection effect, and that the portions of a meteoroid with high porosity will break into smaller pieces. Thus, meteorite studies are likely biased to lower porosities, and so microporosities of asteroids are likely underestimated, and in turn asteroid macroporosities are overestimated.

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References: [1] Toth J. et al. (2015) *Meteoritics & Planet. Sci.* 50:853-863. [2] Kohout T. et al., *Planet. and Space Sci.* 93:96-100. [3] Macke R. J. et al. (2015) *LPSC XLVI* abstract #1716. [4] Bland et al. (1998) *Geochim. et Cosmochim. Acta* 62:3168-3184. [5] Cotto-Figueroa D. et al. (2016) *Icarus* 277:73-77. [6] Lian C. et al. (2011) *Construction and Building Materials* 25:4294-4298.