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Thermal and porosity properties of meteorites: A compilation of published data and new measurements

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Abstract

We report direct measurements of thermal diffusivity and conductivity at room temperature for 38 meteorite samples of 36 different meteorites including mostly chondrites, and thus almost triple the number of meteorites for which thermal conductivity is directly measured. Additionally, we measured porosity for 34 of these samples. Thermal properties were measured using optical infrared scanning method on samples of cm-sizes with a flat, sawn surface. A database compiled from our measurements and literature data suggests that thermal diffusivities and conductivities at room temperature vary largely among samples even of the same petrologic and chemical type and overlap among e.g. different ordinary chondrite classes. Measured conductivities of ordinary chondrites vary from 0.4 to 5.1 W/m/K. On average, enstatite chondrites show much higher values (2.33 – 5.51 W/m/K) and carbonaceous chondrites lower values (0.5 – 2.55 W/m/K). Mineral composition (silicates vs. iron-nickel) and porosity control conductivity. Porosity shows (linear) negative correlation with conductivity. Variable conductivity is attributed to heterogeneity in mineral composition and porosity by intra- and intergranular voids and cracks, which are important in the scale of typical meteorite samples. The effect of porosity may be even more significant for thermal properties than that of the metal content in chondrites.

1. Introduction

General. Thermal properties of meteorites (thermal conductivity, thermal diffusivity, heat capacity, thermal inertia) are essential variables in quantitative modeling of Solar System processes, evolution and state of asteroids and small bodies, e.g. asteroid differentiation processes. Especially, measured thermal conductivity values for meteorites will have a significant impact in the modeling of small body thermal evolution and metamorphism.

Porosity, including intragranular, intergranular, and shock induced porosity, is an important factor affecting thermal properties in asteroids and meteorites along with metal content. Thus, modeling thermal evolution of asteroids requires estimations of their internal structure. Macro porosities show profound variability indicating that the objects range from solid and coherent objects (low macro porosity) to loosely consolidated rubble piles (high macro porosity) (Britt et al. 2002). According to Ostrowski and Bryson (2017), porosity correlates negatively with shear modulus and Young's modulus in particular providing clues on mechanical properties of chondrite bodies. Most of the large mass stony meteorites are products of showers whose fragments are compositionally homogeneous

implying small stony bodies are usually homogeneous and weak rubble piles (Scheeres et al. 2015). While the individual components can be very strong, the asteroid as a whole is very weak (Scheeres et al. 2015).

Consolmagno et al. (2008) report that, in the case of S-type asteroids, macro porosity with significant fractures appears to increase with distance from the Sun. Macro porosity of C-type asteroids is usually higher than that of S-type asteroids. For example, asteroids Bennu and Ryugu have macro porosities around 50%. According to Michel (2014), macro porosity may cause the density between S-type asteroids and their meteorite analogues to differ, while some micro porosity, corresponding to small pores with approximately uniform and isotropic distribution, may be required to elucidate the lower bulk density of C-type asteroids. Unfortunately, there is no direct evidence of the nature of porosity inside an asteroid, even regarding asteroids for which density has been estimated (Michel 2014).

C-type asteroids are extremely dark, while S-type asteroids are bright due to the missing carbon compounds. Typically, dark asteroids are thought to have a bulk density of 1.0–1.3 g/cm³ (e.g. Yeomans et al. 1997) which is lower compared to the 2.0–2.7 g/cm³ bulk densities typical of bright asteroids (e.g. Abe et al. 2006). Comparing the bulk densities of asteroids with those of their assumed meteorite analogues yields porosity estimates for asteroids. Many asteroids appear to have considerable porosities since their bulk densities seem to be well below the grain density of their likely meteorite analogues (Britt et al. 2002). Assuming fractures follow the Weibull distribution (Weibull 1951), in which fractures are assumed to be randomly distributed within the object, the likelihood of fractures increases along with the size of the object. Bryson et al. (2015) noted that scaling the meteorite fractures to the nature of fragmentation of asteroids follows the Weibull distribution. However, Kohout (2009) noted that there is a scale problem in comparing meteorites to asteroids since differences exist on various scales between sample returns, meteorite measurements, and observations of asteroids. The differences are due to sub-mm to km scales of inhomogeneity of asteroids (e.g. mineralogical and structural heterogeneities) and dm to sub-mm scales of inhomogeneity of meteorites (e.g. clasts, inclusions, chondrules) (Kohout 2009).

Thermal properties. Thermal conductivity is a measure of the ability of a material to conduct heat. Thermal conductivity is defined by

$$q = -k\nabla T, \quad (1)$$

where q is the heat flux, k is the thermal conductivity, and ∇T is the temperature gradient. Thermal diffusivity α describes the rate of temperature spread through a material, and it links thermal conductivity with density and specific heat capacity as follows:

$$\alpha = \frac{k}{\rho c_p}, \quad (2)$$

where ρ is the density, and c_p is the specific heat capacity. Thus, thermal diffusivity is directly proportional to thermal conductivity and inversely proportional to specific heat capacity, which is the measure of the amount of heat energy necessary to increase the temperature of a unit quantity of the material by a given temperature interval. Thermal diffusivity has physical relevance in the framework of transient conduction processes. Since thermal diffusivity is a measure of the ability of a material to conduct thermal energy relative to its ability to store thermal energy, high thermal diffusivity translates to high conduction rate relative to heat storage capacity and rapid response to changes in temperature, and thus rapid heat transfer.

Thermal conductivities of meteorites are poorly quantified, and the data of Opeil et al. (2010, 2012) are among the first direct measurements. Due to differences in mineralogy (e.g. amount and types of metal) and physical properties (e.g. density, porosity), thermal conductivity of meteorites varies

significantly. Published thermal conductivity data on meteorites whose porosity has been determined are particularly rare (Flynn et al. 2018). Consequently, measured thermal diffusivity values have been used to determine thermal conductivity values of ordinary chondrites (Yomogida and Matsui 1983, Matsui and Osako 1979). Szurgot and Wojtatowicz (2011) reported thermal diffusivity measurements and Szurgot (2011) reported thermal conductivities for meteorites derived from these measurements in the form of conference abstracts.

Aim of the present study. This study focuses on thermal conductivity, diffusivity, and porosity of chondrites, but data on iron meteorites and a stony iron meteorite are also reported. We used a contactless method to simultaneously measure both thermal conductivity and thermal diffusivity at room temperature. In addition, porosities were determined from densities and volumes acquired with a gas pycnometer and 3D laser scanning measurements. We also provide a compiled dataset of previously reported results on thermal conductivity and porosity properties of meteorites measured to date. We compare our measured data and earlier results, describe differences between meteorite classes, and test relationships between thermal conductivity and porosity, thermal diffusivity and porosity, and thermal conductivity and bulk density. To study the effect of varying porosity and metal content on thermal conductivity, we calculated geometric mean models for meteorites with different theoretical compositions.

1.1 Review of previous measurements

Few direct thermal conductivity measurements are reported in the literature. Matsui and Osako (1979) and Yomogida and Matsui (1983) presented the only systematic work to date regarding thermal conductivities of meteorites. They reported thermal diffusivity measurements of 21 ordinary chondrites under vacuum (<0.1 Pa) at six temperatures from 100 to 350 K using the modified Ångström's method, and used them to calculate thermal conductivities (Eq. 2). They calculated the heat capacities of the samples from the mineralogy of the meteorites and measured grain densities using a helium pycnometer. Bulk densities of samples shaped as rectangular parallelepipeds were calculated from the mass and the volume of the samples, otherwise the modified Archimedean method was used to determine bulk densities. Porosity was calculated from the sample densities. They also studied the effect of weathering on their results and did not find any systematic difference between the physical properties of falls and finds or correlation of physical properties with the amount of rust in their samples, and concluded that their results are not distorted by weathering effects.

In Yomogida and Matsui (1983), the range of thermal conductivities at 300 K is 0.63-3.54 W/m/K for H chondrites and 0.4-2.55 W/m/K for L chondrites. The ranges of conductivity values for these H and L chondrites at 200 K are 0.8-3.9 W/m/K and 0.4-2.3 W/m/K, respectively. Thus, the spread in their results is substantial, and the values for L chondrites overlap with the values of H chondrites, although L chondrites generally have slightly lower conductivities than H chondrites. However, this is not the case considering the reported conductivities in Opeil et al. (2012), where the range of conductivities for both L and H chondrites is broad and significantly overlapping. Note that most of the samples in Yomogida and Matsui (1983) are finds whereas most of the samples in Opeil et al. (2010, 2012) are falls. It is worth noting that all these values are remarkably lower than the conductivities of olivine, pyroxene, and plagioclase (Opeil et al. 2010), and the results by Yomogida and Matsui (1983) show that ordinary chondrites are significantly less conductive than one would calculate simply from the constituent minerals. In addition, Opeil et al. (2012) reported that the measured conductivities of the stony meteorites are lower by as much as an order of magnitude compared to literature values for pure minerals that the meteorite is composed of (Clauser and Huenges 1995). Yomogida and Matsui (1983) observed that some lower-porosity samples have much larger thermal diffusivity than other porous samples. They calculated theoretical conductivities for ordinary chondrites from their normative mineral compositions using thermal conductivity values of individual minerals and the formulae derived by Hashin and Shtrikman (1962), and concluded that

the theoretical values are clearly higher than the measured thermal conductivity of porous and cracked samples.

Opeil et al. (2010, 2012) used a Quantum Design Physical Properties Measurement System, Thermal Transport Option (TTO), to measure thermal conductivity of samples cut into regular parallelepipeds of 2–6 mm dimension (Opeil et al. 2010) and 0.5–1 cm prisms (Opeil et al. 2012) at low temperatures (5–300 K). A heater attached to one end of the sample applies a heat pulse that generates a temperature difference between two thermometers at the sample ends. The sample was measured in a vacuum and the pressure was held to $<1.33 \times 10^{-4}$ Pa. Opeil et al. (2012) stated that the instrument error is generally about 0.01 W/m/K. Their samples included 17 stony meteorites (11 ordinary chondrites, 2 enstatite chondrites, 2 carbonaceous chondrites, 2 basaltic achondrites) and one iron meteorite. While the results of Opeil et al. (2010, 2012) are of higher precision and examine a broader range of temperatures and meteorite types, they agree well with previous studies, where conductivity was determined from diffusivity and modeled heat capacities. They calculated bulk densities based on the regular shapes of the samples, and grain densities were taken from the averages of unweathered meteorites of given class. Porosities were calculated based on the densities.

The difficulty of using a heat pulse by an attached heater lies in establishing a good contact between the heater and the sample. If the contact is insufficient, thermal conductivity will be underestimated (Hofmeister and Pertermann 2008). On the other hand, thermal conductivity measurement using a laser flash method to provide heat via a pulse may lead to erroneous results if the transfer of energy through the crystal by laser photons, rather than phonons is not sufficiently attributed, which leads to overestimation of thermal conductivity (Opeil et al. 2010).

Most studies, e.g. Opeil et al. (2010, 2012), cover temperatures up to about 300 K. Opeil et al. (2012) observed that conductivities remained nearly constant above 100 K as phonon activation energies are reached and the transport of the phonons depends mostly on the occupancy and orientation of cracks, which impede the heat flow consistently at all temperatures. Thus, at around 100 K, the conductivity values reach the highest point and then slowly decrease as temperature increases, and thermal conductivities of meteorites may virtually be assumed constant with temperature above 100 K (Opeil et al. 2012). This agrees with the phonon conduction theory (Debye et al. 1914, Hofmeister et al. 2007), since at low temperatures conductivity is proportional to the T^3 (T is absolute temperature), but at high temperatures to $1/T$. Crystal boundaries, impurities, cracks, and anharmonic coupling affect the temperature, at which the maximum conductivity is reached.

Szurgot and Wojtawicz (2011) measured thermal diffusivities of 18 meteorite samples including eight chondrites using the Laser Flash Method at ambient conditions, at 298 K in 1 atm, and determined the bulk densities using the Archimedean method. They reported the relative errors of diffusivity to be about 1–6%, and density about 1%. Based on the measured thermal diffusivities, Szurgot (2011) derived the thermal conductivities K of the meteorites at room temperature from the relationship $K = DdC_p$, where D is thermal diffusivity, d is bulk density, and C_p is specific heat capacity.

2. Materials and methods

2.1 Materials

The 38 samples of this study represent 36 meteorites including two carbonaceous chondrites, one enstatite chondrite, 29 ordinary chondrites, three irons, and one stony iron meteorite (11 falls and 25 finds) from the meteorite collection of the Finnish Museum of Natural History, University of Helsinki. Chondrites Plainview (H5) and Arcadia (LL6) had two samples. Samples were selected based on their shapes and cut surfaces. The masses of the samples vary from 3.7 g to 403 g with an average of 56 g, sizes from 3.5 cm to 9.3 cm with an average of 6 cm, and volumes from 1.02 cm³ to 125.9 cm³ with an average of 16 cm³. Porosities vary from 2% to 26% with an average of 11%.

All measurements were carried out on samples as such without any extra preparation. All of the meteorite samples used for measurement of thermal properties are cut slabs and some of them are polished, so that the surface requirements of the thermal conductivity scanning instrument are satisfied (see section 2.2).

Varying degrees of terrestrial weathering can be seen in finds, most obviously in the form of iron oxides. In addition, most of the measured falls in this study date back to the nineteenth century and minor weathering effects are probable. Arcadia (LL6), Cope (H5), Covert (H5), Ferguson Switch (H5), McKinney (L4), Neenach (L6), and Plainview (H5) have obvious fractures, which are expected to affect heat transport. Alfianello (L6), Allende (CV3), Beenham (L5), Holbrook (L/LL6), and Valkeala (L6) are partially covered with fusion crust. However, only the measurement surface of Alfianello had fusion crust. Irons Bella Roca (III AB) and Canyon City (III AB) exhibit Widmanstätten pattern. An oval troilite (iron sulfide) inclusion in Bendego (Iron, IC) was not in the measurement path of the thermal conductivity scanning instrument.

2.2 Thermal properties

Thermal conductivity and diffusivity were measured using TCS Optical scanner (The Thermal Conductivity and Diffusivity Meter, TCS Lippmann & Rauen GbR), which applies a high precision, noncontact method based on optical scanning (e.g. Popov et al. 1985). The optical scanning technology is based on scanning a sample surface with a focused, mobile, and continuously operated near-point-like optical heat source conjointly with infrared temperature sensors. The sensor “cold” is aligned exactly to the scanning line and measures the temperature before heating, while sensor “hot” measures the temperature after heating approximately 7 millimeters off the scanning line. Thermal properties are determined by comparing the temperature differences measured on standard samples with known thermal properties with the temperature differences measured on the sample. Thermal conductivity and thermal diffusivity were measured at room temperature, and the precision of the instrument is 3% for a confidential probability of 0.95 for conductivity measurements and 5% for thermal diffusivity measurements. Measurement range for conductivity is from 0.2 W/m/K to 25 W/m/K and for thermal diffusivity from 0.6 mm²/s to 3.0 mm²/s.

Popov et al. (1999) compared three different laboratory methods including the method used in this study, as well as half-space line source and divided bar methods for thermal conductivity measurements based on an extensive collection of rock samples. Regardless of the inhomogeneity of thermal conductivity and high anisotropy of the samples, the results of the different methods were found consistent.

With TCS, it is possible to measure thermal conductivity and thermal diffusivity simultaneously using TC+TD –mode. As results of the scanning, profiles of thermal properties along the scanning line, inhomogeneity of thermal properties, and components of the thermal properties tensor for anisotropic solids (anisotropy) are obtained in addition to the recorded values for thermal conductivity and diffusivity.

The measured samples need to have a flat or a cylindrical surface, and the minimum length along the scanning line is four centimeters. The minimum thickness depends on the sample’s thermal conductivity, and the minimum width is equal to the minimum thickness. These can be determined from the nomograms in the instrument documentation. Acceptable sample surface is smooth with maximum spatial deviations of ± 0.5 mm. All of the measurement surfaces of our samples complied the instrument requirements.

In order to homogenize the sample surface emissivity for the TCS scanning, the surface has to be prepared black. Usually this is done with black paint, but in the case of meteorite samples it is not permitted. Therefore, Scotch® Magic™ Tape was applied to prepare the meteorite samples, since it is thin enough and easy to apply and remove from the surface without damaging the sample. We tested the effect of the tape and the paint on thermal conductivity by measuring test samples with

known thermal conductivity using paint, as well as both tape and paint and the results were consistent. The tape was carefully attached to the sample preventing any air pockets from forming underneath the tape. After this, the tape was colored. We tested different types of paints to minimize the influence of varying optical reflection coefficients, and the best results were obtained using gouache paint with varnish. Gouache provides a deep black and matte finish, which is suitable to prevent optical reflection. In addition, gouache has the advantage of being very opaque with only a small amount of coating. It also dries quickly and provides an even surface regarding thickness and roughness with no brush marks. The thickness of the colored tape is approximately the same as that of the tape itself; 50-60 μm . Using a coat of varnish provides a scratch resistant surface and prevents fingerprints.

Thermal conductivity and thermal diffusivity were measured four times for each sample to test reproducibility, and the average of these values is reported for every sample. Thermal measurements were conducted in two orthogonal directions for 23 samples to see if anisotropy occurs in conductivity. Some of the samples lack porosity determination as their sizes exceeded the volume of the sample cell of the gas pycnometer.

2.3 Porosity

We measured the masses of the meteorites using Ohaus Scout® Pro scale with maximum capacity of 400 g and resolution of 0.01 g. Mass error is considered insignificant comparative to volume error. We used a gas pycnometer, Quantachrome Ultrapyc 1200e, which provides a non-destructive method, to measure the grain volume of the meteorite samples. The instrument measures the volume impassable to nitrogen, which corresponds to the “grain volume” of the sample. The sample cells are up to 135 cm^3 . It is noteworthy that the sample volume and preparation influence the precision and reproducibility. For example, the temperature of the sample should be similar in subsequent measurement. The instrument automatically takes ten measures and reports the average value of the grain volume and the average volume standard deviation. Grain density of the sample was calculated from the measured grain volume and the sample mass. Wilkison et al. (2003) performed an analysis of a typical pycnometer, and reported that when estimating porosity, the grain volume error dominates the uncertainty and is relatively higher in smaller sized samples. The accuracy and repeatability of Quantachrome Ultrapyc 1200e are $< \pm 0.02\%$ and $< \pm 0.01\%$, respectively, for sample cell sizes of 135 cm^3 and 50 cm^3 . For the smallest sample cell of 10 cm^3 the accuracy and repeatability are $< \pm 0.03\%$ and $< \pm 0.015\%$, respectively.

3D laser scanning possibly provides the least invasive technique in determining the bulk volume of a meteorite. As a method, it is non-destructive with no physical or chemical contamination of the meteorite. We used triangulation laser scanner, NextEngine 3D Scanner Ultra HD model 2020i, for the measurements. First step was to acquire image data. Second step was to build a volumetric 3D model of the meteorite. Finally, Geomagic Verify Viewer program was used to determine the volume of the 3D model. Bulk density was calculated based on the measured bulk volume. Theoretical 1- σ uncertainties in volumetric measurements using NextEngine 3D laser scanner at high resolution are about 0.4% for a 1 cm^3 sample and decrease with sample size to 0.02% for samples above 40 cm^3 (Macke et al. 2015).

Erroneous textures and morphologies may occur especially in 3D scanning at high resolutions, if the distance of the meteorite from the scanner is not in the ideal range of the instrument. The sizes of the meteorites in this study did not appear to present problems during scanning. However, sharp edges and angles may create partially obstructed paths for the laser planes, and this may lead to weak reflections that may not be detected. This in turn leads to visible scars in the 3D model. Fusion crust present in some of the meteorites may result in detection of only a weak specular reflection at some incident angles of the laser planes, which may cause holes in the point cloud data and influence image alignment. In addition, the 3D model building process may lead to distortion of volumes if trimming of image edges is excessive or insufficient.

Porosity of the samples was calculated from the acquired grain and bulk density. The uncertainty of porosity was determined by calculating the combined uncertainty using summation in quadrature, or the root sum of the squares.

2.4 Geometric mean models

We calculated theoretical models to predict the thermal conductivity of ordinary chondrites. McSween et al. (1991) reported the average and standard deviations of normative minerals for ordinary chondrite classes. Generalizing, two thirds of the bulk composition of ordinary chondrites is comprised of olivine and hypersthene, which belongs to the group of orthorhombic pyroxenes, and metal or Fe-Ni alloys (kamacite and taenite) and sulfide (troilite) constitute most of the remainder.

Normative mineralogies provide a feasible estimation of the modal mineralogy for ordinary chondrites (Dodd 1981, McSween et al. 1991). Chondrule abundance in ordinary chondrites is 60-80 vol%, and matrix abundance 10-15 vol% (Weisberg et al. 2006). Both chondrules and matrix are dominated by olivine and pyroxene.

We calculated thermal conductivities for model compositions of H, L, and LL chondrites by geometric mean of the relative abundances of olivine (Ol), pyroxene (orthopyroxene (OPy) + clinopyroxene (CPy)), plagioclase, troilite, Fe-Ni, porosity, and the respective thermal conductivities as follows:

$$\lambda_{geo} = \prod \lambda_i^{n_i}, \quad (3)$$

where λ_i is the thermal conductivity of the i-th component and n_i its volume fraction with $1 = \sum n_i$.

The ratios Ol/Py and OPy/CPy, and the volume percent of Fe-Ni were kept constant within each ordinary chondrite class, while the volume percent of porosity changed. The Ol/Py ratio is 1.2, 1.6, and 2.5 for H, L, and LL chondrites, respectively (Van Schmus 1969, McSween et al. 1991). The OPy/CPy ratio is 5.7, 4.0, and 3.5 for H, L, and LL chondrites, respectively (Van Schmus 1969, Yomogida and Matsui 1983). Reported weight percentages in Van Schmus (1969) and Yomogida and Matsui (1983) were converted to volume percentages using the density of each mineral phase in Yomogida and Matsui (1983).

The volume percent of plagioclase varies only little in ordinary chondrites (Hutchison 2004). In addition, troilite or FeS content is fairly uniform in H, L, and LL chondrites (Hutchison 2004). Thermal conductivities for iron-nickel alloys from Ho et al. (1978) in our model compositions of H, L, and LL chondrites are based on the average metal nickel concentrations of H, L, and LL chondrites of 10%, 14%, and 30%, respectively (Reisener and Goldstein 2003, Jarosewich 1990). Variables used in our models for different ordinary chondrites are presented in Table 1. To compare our calculated conductivities of model compositions in ambient and vacuum conditions, we used thermal conductivity of air of 0.024 W/m/K and 3.0×10^{-6} W/m/K, respectively.

2.5 Correction of thermal conductivities measured in ambient air to low pressure equivalents

The thermal conductivity of a meteorite depends on the conductivity of its mineral constituents, the conductivity of the gas/fluid in its pore space, and the geometry and degree of the porosity. The pressure of gas in the pore space has a strong effect on thermal conductivity (e.g. Fountain and West 1970), which can be explained with regard to the mean free path of molecules in the gas (Fujii and Osako 1973). Since we measured thermal properties in ambient air and Opeil et al. (2010, 2012) and Yomogida and Matsui (1983) at significantly lower pressures, we subtracted the effect of air in the pore space from our results in order to get comparable values. Assuming the effective shape of pores is spheroidal, we can calculate the average aspect ratio of pores using the theoretical expression of

Walsh and Decker (1966). The relation between the effective thermal conductivity at 1 atm (K_e) and the thermal conductivity of the solid (K_s) and fluid in the pores (K_f) is

$$\frac{K_s - K_e}{K_s - K_f} = \frac{p}{3} \frac{1}{K_f/K_e + \frac{1}{2}(\pi\alpha)}, \quad (4)$$

where p and α are the porosity and the aspect ratio of the pores, respectively (Fujii and Osako 1973, Walsh and Decker 1966). Considering vacuum and lower temperature conditions, K_f can be neglected, and the effective thermal conductivity in vacuum (K_v) is then

$$\frac{K_s - K_v}{K_s} = \frac{p}{3} \frac{2}{\pi\alpha}, \quad (5)$$

(Walsh and Decker 1966, Fujii and Osako 1973). We calculated the effective conductivity in vacuum from the model composition curves that corresponds to the porosity of our samples, and used Eq. 5 to estimate a value of the aspect ratio of pores of our samples. The aspect ratio of pores increases polynomially with increasing porosity (Fig. 1), and thermal conductivity is highly sensitive to the aspect ratio of pores. Using the values of measured conductivity in ambient air, thermal conductivity of ambient air, porosity, and acquired aspect ratio of pores we can calculate the thermal conductivity of the solid and the effective thermal conductivity of our samples under vacuum conditions (Eqs. 4 and 5). Specific heat capacity of our samples is calculated using the measured thermal conductivity, diffusivity, and density in ambient air. Thermal diffusivities of our samples under vacuum conditions are calculated using the thermal conductivity under vacuum conditions, bulk density and specific heat capacity (Eq. 2). The calculated aspect ratio of pores, thermal diffusivity, and thermal conductivity at low pressure are reported in Table 2.

3. Results

The results of this study and literature data are compiled in Table 2. Error margins are reported for our data and when given in other studies. According to our data, thermal conductivity of chondrites is 0.22–3.10 W/m/K. In the case of finds, the range is 0.72– 3.10 W/m/K, and in the case of falls 0.22–2.37 W/m/K. Thermal diffusivities are 0.30–1.09 mm²/s and 0.05–0.72 mm²/s for chondrite finds and falls, respectively. It is important to note that Table 2 contains thermal conductivities measured at 200 K and 300 K, and that the results are marginally higher (<0.4 W/m/K) for ordinary chondrites at 300 K (Ostrowski and Bryson 2019). Calculated average thermal conductivities and porosities for chondrite classes from data in Table 2 representing 300 K and vacuum conditions are presented in Table 3.

Thermal conductivities and porosities of all meteorites, including both falls and finds, in Table 2 are presented in a histogram in Fig. 2. In this study, the porosity of the measured chondrites is 2.4 – 19.7% for finds and 5.2 – 22.6% for falls. Figs. 3 and 4 show the overlap among ordinary chondrites' thermal conductivities.

Our data and previously published thermal conductivity values and porosities for chondrite falls are presented in Fig. 5. We found a linear correlation between thermal conductivity and porosity with R-squared value of 0.88 for chondrite falls in our results (Fig. 5). The correlation for chondrite falls in all data is weaker with R-squared value of 0.61. Outliers, E chondrites Abee (EH4, breccia, see section 4, Data) and Pillistfer (EL6), are excluded from the correlation. In addition, ordinary chondrite Alfianello (L6) is excluded because of the measurement uncertainty due to fusion crust present on the measurement surface. Some of the chondrites in this study have two results measured in orthogonal directions, and the correlation contains their average value.

We observed a linear relationship between thermal conductivity and bulk density over the range of different classes of chondrite falls with R-squared value of 0.64 and 0.62 for our data and all data, respectively (Fig. 6). Chondrites Abee, Pillistfer, Cold Bokkeveld, and Alfianello are not included in the correlation. Fig. 7 shows the correlation between thermal diffusivity and porosity of falls in our results and all the data with R-squared values of 0.85 and 0.70, respectively. Abee and Alfianello are excluded from the correlation.

Geometric mean models for model compositions of H, L, and LL chondrites are presented in Figs. 8 and 9. Fig. 10 illustrates the effect of varying porosity and metal content at 1 atm, when the ratio of olivine is 1:1, and thermal conductivities are calculated for different theoretical compositions of meteorites. Fig. 11 illustrates how thermal conductivities and porosities in Table 2 fit to the calculated thermal conductivities for model compositions of ordinary chondrite classes.

4. Discussion

Data. Our results are within the range (0.4–5.5 W/m/K) of thermal conductivities of chondrites previously reported by Yomogida and Matsui (1983), Opeil et al. (2010), and Opeil et al. (2012). However, our results do not extend to the values above 3.1 W/m/K. Thermal conductivities of enstatite chondrites Abee (Opeil et al. 2010) and Pillistfer (Opeil et al. 2012) are much higher (>5 W/m/K) than the highest conductivities measured in this study for McKinney (L4) and Ransom (H4). In Opeil et al. (2010), the reported, directly measured, thermal conductivity of Abee at room temperature is close to that of olivine and enstatite (c. 5 W/m/K). Thermal conductivity of the sample of Abee measured in this study is 2.33 W/m/K at 1 atm (0.63 W/m/K at low pressure), which is significantly lower. However, Abee is a breccia consisting of both metal-rich and metal poor clasts that may be very large in size (Sears et al. 1983), and the size of these clasts may exceed the size of the sample that Opeil et al. (2010) measured. The sample measured in this study contains clasts that are several centimeters in size. Jarosewich (1990) reported enstatite chondrites being commonly heterogeneous on scales larger than 10 g (i.e. about 1.4 cm). These observations and the difference in measured conductivities of Abee in different studies indicate that our result may not sample the entire meteorite or the enstatite parent body.

In addition, Opeil et al. (2010) measured a porosity of 3.0% for their sample of Abee, while the determined porosity for the sample of Abee in this study is remarkably higher, 22.6%. Especially, the difference in measured grain densities is high, which may reflect the amount of metallic Fe-Ni in the samples. It is possible that the large clasts of our sample of Abee are metal-rich, since the measured grain density is notably high (4.4 g/cm³) whereas the grain density in Opeil et al. (2010) is lower (3.6 g/cm³).

Iron components in chondrites are dimensionally heterogeneously distributed and have high thermal conductivity which may result in differences of the average conductivity of the sample and between samples of varying size of the same meteorite. Since the reported thermal conductivity is a mean value in this study, the lower thermal conductivity of our sample of Abee may be explained by the thin scanning line whose path encountered mostly silicate material or metal-poor clasts. Indeed, the difference of the minimum and maximum thermal conductivity recorded in the measurement path is notably large, and the value of inhomogeneity coefficient is high. In addition, the instrument recorded a high value of coefficient of variation. Hence, there is very large heterogeneity and possibly anisotropy in conductivity in our sample of Abee. It seems that the difference in grain densities between our sample of Abee and the sample in Opeil et al. (2010) is due to Fe-Ni content whereas the difference in thermal conductivity may be attributed to porosity. Plots in Fig. 10 agree with this notion.

Thermal conductivity evidently depends on the quantity of iron in the meteorite. Bearing in mind the different iron contents in H, L, and LL chondrites, one may assume that H chondrites have the highest average thermal conductivity and LL chondrites the lowest. In the compiled data, this trend

persists within the different classes of chondrites (Fig. 4 and Table 3). However, in our data this trend is not as obvious but slightly obscured (Fig. 3 and Table 3). Consolmagno et al. (2008) report average porosities of 7.0%, 5.6%, and 8.2% for H chondrite falls, L chondrite falls, and LL chondrite falls, respectively. In our results, L chondrites have the lowest average porosity of these classes and the highest average thermal conductivity of ordinary chondrites (Fig. 3 and Table 3).

Thermal diffusivities and conductivities are very different and scattered even among samples of the same chemical and petrologic type (Figs. 3 and 4), which suggests that the physical structure of the stony meteorites strongly affects the thermal conductivity (Ostrowski and Bryson 2019). This is observed for both falls and finds of H, L, and LL chondrites in this study. L6 chondrites have the largest variation in thermal conductivity in our data (Fig. 3), and in the compiled data, the largest variation is found within H5 chondrites (Fig. 4). Although meteorites with different petrologic types have nearly the same chemical composition, there are only few common features among them. This raises a question whether the sample sizes of 4-10 cm are too small to represent the whole meteorite.

Measurements of thermal properties of different samples of the same meteorite demonstrate the effect of heterogeneity in the cm-scale. For example, we measured a difference of 0.41 W/m/K in conductivity for different samples of Arcadia (LL6). In addition, we measured 21 ordinary chondrites in two orthogonal directions, and found significant differences for Ferguson Switch (H5, $\Delta k=0.45$ W/m/K), McKinney (L4, $\Delta k=0.27$ W/m/K), and Bath Furnace (L6, $\Delta k=0.21$ W/m/K). Opeil et al. (2012) reported differences in thermal conductivity of Bath Furnace and Holbrook when measured in two orthogonal directions and in different samples of the same meteorite. While we observed a difference in thermal conductivity of Bath Furnace when measured in two orthogonal directions, there was no significance difference in Holbrook when measured in two directions. As Opeil et al. (2012) noted, the differences are greater than any measurement error, and must portray structural differences in the conductivity within the samples, including significant anisotropy. Thus, the relationship between thermal conductivity and porosity or mineralogy cannot be simple, as the conductivity changes with the orientation of cracks and pores (Opeil et al. 2012).

The results of Yomogida and Matsui (1983) imply that thermal conductivity decreases when porosity increases. Opeil et al. (2012) showed that, in general, thermal conductivity is linearly inversely proportional to porosity, despite the fact that the relationship does not include the anisotropic effects of shock-induced cracks. However, there are samples, e.g. L6 chondrite Kunashak (Yomogida and Matsui 1983) and L5 Sevrukovo (this study), that are inconsistent with this tendency. Our data agree well with the linear inverse relationship between thermal conductivity and porosity at room temperature (Fig. 5). However, the correlation in all the data is weaker. Recall that our data are the corrected thermal conductivities which are sensitive to the calculated aspect ratio of pores. It is possible that the correlation in all the data would be stronger if our data were measured in vacuum conditions. In addition, data dispersion may be due to different measurement methods. Additionally, samples measured in this study are large in size and show heterogeneity in cm-scale, which consequently makes the range of the dataset larger compared to the range of a dataset with similar sized samples.

Szurgot (2011) observed a linear relationship between thermal conductivity and bulk density over the range of stony meteorites, stony iron meteorites and iron meteorites. Our data, as well as all the data, agree reasonably well with this trend within the various classes of stony meteorite falls (Fig. 6). In addition, our data and all the data agree well with the relationship between thermal diffusivity and porosity observed by Yomogida and Matsui (1983) (Fig. 7).

Theoretical modeling of conductivity. Our theoretical models give only rough assumptions of the thermal conductivities with the main aim to describe the effects of porosity and metal content on thermal conductivity. However, geometric mean model demonstrates a feasible agreement between calculated and measured bulk thermal conductivity (Fuchs et al. 2013). Geometric models in Fig. 10 for different theoretical compositions of meteorites show, for example, that as metal content increases from 10% to 20%, thermal conductivity at porosity of 25% increases 0.35 W/m/K. In comparison, if

porosity increases from 10% to 20%, thermal conductivity at metal content of 25% decreases 1.72 W/m/K. At porosity of 2%, the thermal conductivity increases 1.17 W/m/K when metal content increases from 10% to 20%, and at metal content of 2%, conductivity decreases 1.02 W/m/K when porosity increases from 10% to 20%. In summary, if porosity remains the same, especially for low porosity values, and metal content increases from 2% to 25% the change in thermal conductivity is smaller compared to the change in conductivity when metal content remains the same and porosity increases from 2% to 25%.

The model results indicate that, for each type of ordinary chondrites, thermal conductivity decreases as porosity increases (Fig. 11). Thus, decreasing porosity facilitates the development of more thermal paths. The decrease in thermal conductivity is more rapid when porosity is lower than about 10%. Especially for H chondrites, the thermal conductivity decreases more rapidly at lower porosities and thermal conductivity reaches the highest value of c. 4.4 W/m/K at zero porosity, which is nearly four times larger compared to thermal conductivity at porosity of 25% (Fig. 9). The decrease of thermal conductivity is nearly linear at low porosities for H, L, and LL chondrites (Fig. 11). Thermal conductivity of H chondrites decreases the most when porosity increases from 2% to 25% and thermal conductivity of LL chondrites the least. In comparison to H chondrites, the decrease of thermal conductivity for LL chondrites with incorporated porosity is not as significant, and the highest value of conductivity is c. 3.9 W/m/K at zero porosity. For the same porosity, the thermal conductivities of different ordinary chondrites always act in accordance with the order of $H > L > LL$ due to the composition of the ordinary chondrites.

Measured conductivities and porosities in Opeil et al. (2010, 2012) and Yomogida and Matsui (1983) fit reasonably well to the calculated thermal conductivity curves for model compositions of ordinary chondrites in Fig. 11. Recall that their measurements were conducted under vacuum and our results are obtained at 1 atm. Thus, air in the pore space of our samples has thermal conductivity of c. 0.024 W/m/K, which is considerably higher compared to conductivity of air in vacuum, and this leads to higher conductivities when measured in room conditions. However, our results corrected to low pressure fit moderately well to the curves. Aberration of the calculated curves from the measured results may be due to the simplified model, which only considers the contents of iron-nickel, olivine, pyroxene, plagioclase, and troilite with varying porosity. The composition of olivine, and thus the estimated thermal conductivity of olivine, was constant in the calculations for different ordinary chondrite classes. It is important to note that the geometry of the pore space in our samples is not known and the calculated values of the aspect ratio of pores and conductivity in vacuum based on the model composition curves are suggestive. There is definitely a need to investigate the geometry of the pore space more deeply.

Effect of macro porosity and structure. The heterogeneity and isotropic nature of asteroids derive from macro porosity. Large fractures and voids are probably caused by impacts and represent the zones of structural weakness along which meteorites break apart during impacts. These features are large on the scale of meteorites. Creation of cracks is possible with small change of porosity, and impacts do not necessarily affect the sample porosity (Yomogida and Matsui 1983). It has been shown that porosity of shocked and unshocked chondrites is nearly the same (Anders 1964, Consolmagno et al. 2008). Thus, impacts affect macro porosity, but the effect on micro porosity of meteorites may not be significant, and meteorites' thermal properties may not be altered significantly due to the impact history and thus represent thermal properties of material within asteroids. However, it is likely that the macro porosities of asteroids are considerable, since their bulk densities appear to fall well behind the grain density of their probable meteorite analogues. This indicates asteroids have also lower thermal conductivities compared to their meteorite analogues. Thus, modeling the thermal evolution of an asteroid relies heavily on assumptions of the internal structure of asteroids and how to use the thermal data obtained from meteorites.

The basic material of ordinary chondrite parent bodies is strong since it contains welded silicates and metal providing a fortifying structural mesh, which is often adjoined if the ordinary chondrite has

experienced re-melting and metamorphic processing (Scheeres et al. 2015). Ordinary chondrites often contain large zones of pre-existing weakness. Although the nature of fracturing varies, chondrites generally display random fractures notwithstanding the meteorite texture (Bryson et al. 2015). In addition, some chondrites exhibit a distinct network of fractures (Bryson et al. 2015). Further research on the geometry of pore space in meteorites would be an interesting extension considering thermal properties of meteorites.

Since our samples are of several centimeters size, some of them exhibit cracks to varying extent causing heterogeneity and possibly anisotropy. Thus, larger heterogeneity is expected compared to millimeter-sized samples in previous studies. However, it has been observed in non-shocked ordinary chondrites that cracks are the minor contribution to porosity, with around two-thirds of porosity coming from inter-granular voids (Sasso et al. 2009). Also, Consolmagno et al. (2008) reported that only a very weak correlation between porosity and shock state has been found. Considering the complex impact history of asteroids and assuming the random orientation of cracks, an average correlation between porosity and thermal conductivity should feasibly describe the typical conductivity within an asteroid (Opeil et al. 2012).

In studies by Consolmagno and Britt (1998), Flynn et al. (1999), and Wilkison et al. (2003), no correlation between porosity and petrologic grade was found indicating porosity is not dependent on the heating process. It is expected that metamorphism alters porosity and pores may be generated after metamorphism. Considering the data in this study, the porosity of H chondrites somewhat decreases with increasing metamorphic temperature. This suggests raising temperature stimulates compaction and recrystallization. However, there are significant variations in porosity within the same petrologic types. On the other hand, the porosity of L chondrites appears to increase with increasing metamorphic temperature. Since there is no obvious correlation between petrologic type and porosity, it is feasible that impact shocking has reworked the material.

Effect of weathering. In analyzing meteorites, especially meteorite finds, weathering effects, such as metal oxidation, and the degree of weathering must be assessed, since weathering affects the meteorite's primordial composition. Considering ordinary chondrites, Gibson and Bogart (1978) and Bland et al. (1998) recognized a depletion in Si and Mg with increasing weathering, while the elemental concentration of Fe was not significantly altered (Bland et al. 2006). Al-Kathiri et al. (2005) observed mobilization of Ni and Co in connection with breakdown of Fe-Ni metal. Fe-Ni metal, troilite, and mafic silicates expose ordinary chondrites to rusting, which causes the most evident weathering products on meteorites. As metals oxidize, their thermal conductivities decrease, and thus the conductivity potential of meteorites will weaken. Ordinary chondrite falls have quite large porosities of 11-15% (Wasson 1974) with an average range of 8-9.5% (Flynn et al. 2018). Ordinary chondrite finds have porosities of 2.8-5.8% (Macke 2010). Oxidation of metal induces grain volume expansion (Buddhue 1957), and thus, porosity may reduce (Bland et al. 2006). This translates to falls having higher porosities than finds. There are many similarities between ordinary and carbonaceous chondrite weathering. It is evident that meteorite finds are weathered to varying degrees. However, falls, especially carbonaceous chondrite falls, are also vulnerable to alteration by terrestrial environment because of e.g. a large proportion of fine-grained matrix and abundance of volatile elements (Bland et al. 2006). For example, Abreu and Brearley (2005) have concluded that the veins in CV3 chondrite fall Vigarano are terrestrial in origin.

Bland et al. (1996a, b, 1998, 2000) examined a quantitative index of alteration for ordinary chondrites based on applying Mössbauer spectroscopy to determine the relative abundances of Fe⁰ in metal, Fe²⁺ in sulfide and silicate, and Fe³⁺ in weathering products (Hutchison 2004). The amounts of oxidized Fe in weathered ordinary chondrites can be linked with particular outset compositions since the amounts of Fe⁰ and Fe²⁺ are well known in ordinary chondrite falls (Hutchison 2004). A mineralogic alteration index (MAI) is based on studies to qualify (McSween 1979) and quantify the extent of alteration in CM falls (Browning et al. 1996). There is a strong positive correlation between MAI and the year of fall, and the more altered a meteorite is the older the fall is, but it is not clear if

MAI indicates terrestrial or pre-terrestrial alteration (Bland et al. 2006). Although MAI is established by studies on carbonaceous chondrites, it may have significance on ordinary chondrites given the similarities between their weathering. Many of the falls measured in this study date back to the nineteenth century, and these assumptions need to be kept in mind when analyzing the data.

5. Conclusions

Our results cover almost the entire range of thermal conductivities of chondrites previously reported. On average, enstatite chondrites show much higher conductivities compared to ordinary chondrites. Carbonaceous chondrites have lower metal contents and higher average porosities than ordinary chondrites, and their conductivities fall in the lower end of the range of conductivities of ordinary chondrites. Based on the decreasing metal content in ordinary chondrite classes (H>L>LL), one may expect H chondrites to have the highest average conductivity and LL chondrites the lowest. This trend shows in the compilation of our results and literature data.

Our results confirm earlier work on the inverse linear relationship between porosity and thermal conductivity of meteorites. We found a reasonable linear correlation between thermal conductivity and bulk density of chondrite falls in addition to inverse relationship between thermal diffusivity and porosity of chondrite falls. Thermal conductivity curves for model compositions of ordinary chondrites calculated by geometric mean fit reasonably well to the measured conductivities and porosities in this study and previous studies.

Measurements of different samples of the same meteorite demonstrate the effect of heterogeneity in the cm-scale. Differences between thermal conductivities of the same sample measured in orthogonal directions indicate porosity may largely govern the conductivity. The differences must portray variation in conductivity with the geometry of the pore space, since they exceed any measurement error.

Thermal diffusivities and conductivities are very different even among samples of the same chemical and petrologic type, which also suggests that the physical structure of the stony meteorites strongly affects the thermal conductivity. Applied hypothetical models of H, L, and LL compositions with varying porosity and metal content indicate that internal structure (i.e. porosity) of the meteorite may affect the thermal conductivity even more compared to the metal content of the meteorite. However, the effects of porosity and metal content cannot be completely separated. The impact history may not have altered the micro porosity of the meteorite, but large enough samples may exhibit random cracks that evidently affect thermal conductivity and cause heterogeneity and possibly anisotropy. Our samples are of several centimeters size, and exhibit cracks in some cases. However, it has been observed that cracks contribute only little to porosity.

Meteorites are primarily composed of minerals that are typical in terrestrial rocks, and models of thermal evolution of asteroids often utilize thermal properties of these minerals to estimate e.g. thermal conductivities. Previous measurements of thermal conductivities of meteorites, as well as the results in this study, show that thermal conductivities of pure minerals comprising the meteorites are substantially higher compared to the measured bulk conductivities of meteorite samples. Thermal properties and porosity of meteorites are intimately coupled and should be studied jointly.

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Table I. Variables in geometric mean models in this study for H, L, and LL chondrites.

Mineral	H chondrites		L chondrites		LL chondrites	
	Thermal conductivity (W/m/K)	Vol%	Thermal conductivity (W/m/K)	Vol%	Thermal conductivity (W/m/K)	Vol%
Olivine	4.3 ^a	varying	4.3 ^a	varying	4.3 ^a	varying
Orthopyroxene	3.9 ^a	varying	3.9 ^a	varying	3.9 ^a	varying
Clinopyroxene	4.6 ^a	varying	4.6 ^a	varying	4.6 ^a	varying
Plagioclase	1.9 ^a	10 ^b	1.9 ^a	10 ^b	1.9 ^a	10 ^b
Troilite	4.6 ^a	3.5 ^b	4.6 ^a	3.5 ^b	4.6 ^a	3.5 ^b
Fe-Ni metal	28.1 ^c	8.4 ^d	24.8 ^c	4.1 ^d	14.6 ^c	2.0 ^d

^a Yomogida and Matsui (1983)

^b Van Schmus (1969)

^c Ho et al. (1978)

^d Vernazza et al. (2015)

Table II. Thermal properties, densities and porosities of meteorites in this study and literature data.

Meteorite	Class	Fall	Weathering grade**	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Thermal diffusivity (mm ² /s)	Corrected thermal diffusivity (1.33 x 10 ⁻⁴ Pa) (mm ² /s)	Thermal conductivity (W/m/K)	Aspect ratio of pores	Corrected thermal conductivity (1.33 x 10 ⁻⁴ Pa) (W/m/K)	Specific heat capacity (J/kgK)	Temp. (K)	Notes
Soini et al. (this study)														
Kainsaz	CO3.2	Fall		3.2	3.4	7.4 ± 0.6	0.94	0.68	2.55 ± 0.06 ^a	0.024	1.85	853 ^d	296	
Allende	CV3	Fall		2.9	3.7	21.7 ± 0.5	0.45	0.08	1.21 ± 0.01 ^a	0.048	0.22	925 ^d	296	
Allende*	CV3	Fall		2.9	3.7	21.7 ± 0.5	0.35	0.06	1.21 ± 0.02 ^a	0.048	0.22	1189 ^d	296	
Abee	EH4	Fall		3.4	4.4	22.6 ± 1.4	1.39	0.37	2.33 ± 0.09 ^a	0.050	0.63	491 ^d	296	
Metsäskylä	H4	Find		3.2	3.8	15.8 ± 1.9	0.77	0.35	2.43 ± 0.07 ^a	0.037	1.10	977 ^d	296	
Orimattila	H4	Find		3.4	3.6	3.5 ± 1.0	1.18	1.02	2.48 ± 0.05 ^a	0.019	2.14	614 ^d	296	1
Orimattila*	H4	Find		3.4	3.6	3.5 ± 1.0	1.06	0.92	2.57 ± 0.16 ^a	0.019	2.23	711 ^d	296	1
Ransom	H4	Find		3.6		6.1 ± 0.7	1.33	1.09	3.64 ± 0.12 ^a	0.022	2.99	761 ^d	296	1
Ransom*	H4	Find		3.6		6.1 ± 0.7	1.09	0.89	3.75 ± 0.13 ^a	0.022	3.09	959 ^d	296	1
Seneca	H4	Find		3.1	3.9	19.7 ± 1.1	0.87	0.30	2.41 ± 0.16 ^a	0.045	0.83	897 ^d	296	
Seneca*	H4	Find		3.1	3.9	19.7 ± 1.1	0.96	0.35	2.69 ± 0.06 ^a	0.045	0.99	908 ^d	296	
Cope	H5	Find		3.4	3.6	7.7 ± 0.9	0.96	0.70	2.70 ± 0.07 ^a	0.025	1.96	843 ^d	296	
Cope*	H5	Find		3.4	3.6	7.7 ± 0.9	0.96	0.70	2.79 ± 0.16 ^a	0.025	2.05	871 ^d	296	
Covert	H5	Find		3.2	3.6	12.6 ± 1.0	0.93	0.53	2.63 ± 0.06 ^a	0.032	1.49	896 ^d	296	
Covert*	H5	Find		3.2	3.6	12.6 ± 1.0	0.93	0.52	2.58 ± 0.14 ^a	0.032	1.46	880 ^d	296	
Ferguson Switch	H5	Find		3.3	3.7	9.3 ± 1.0	0.99	0.67	2.72 ± 0.13 ^a	0.027	1.85	829 ^d	296	
Ferguson Switch*	H5	Find		3.3	3.7	9.3 ± 1.0	1.09	0.77	3.25 ± 0.29	0.027	2.30	899 ^d	296	
Plainview 1	H5	Find		3.5	3.8	9.3 ± 1.0	1.00	0.72	3.47 ± 0.14 ^a	0.027	2.51	991 ^d	296	
Plainview 1*	H5	Find		3.5	3.8	9.3 ± 1.0	0.95	0.68	3.33 ± 0.09 ^a	0.027	2.38	1004 ^d	296	
Plainview 2	H5	Find		3.5	3.9	10.9 ± 1.1	1.02	0.65	2.83 ± 0.07 ^a	0.029	1.80	803 ^d	296	
Plainview 2*	H5	Find		3.5	3.9	10.9 ± 1.1	1.00	0.64	2.89 ± 0.13 ^a	0.029	1.85	837 ^d	296	
Slovak	H5	Find		3.4	3.8	12.3 ± 1.0	1.35	0.79	2.72 ± 0.09 ^a	0.032	1.59	600 ^d	296	
Slovak*	H5	Find		3.4	3.8	12.3 ± 1.0	1.23	0.72	2.72 ± 0.08 ^a	0.032	1.59	656 ^d	296	
Travis County	H5	Find	W3	3.3	3.9	15.8 ± 1.2	1.29	0.51	1.83 ± 0.05 ^a	0.038	0.72	432 ^d	296	
Cobija	H6	Find		3.4	3.8	11.2 ± 1.2	0.82	0.53	3.12 ± 0.11 ^a	0.030	2.01	1121 ^d	296	
Holbrook	L/LL6	Fall		3.1	3.7	14.3 ± 0.6	0.46	0.18	1.44 ± 0.07 ^a	0.035	0.56	1001 ^d	296	
Holbrook*	L/LL6	Fall		3.1	3.7	14.3 ± 0.6	0.41	0.16	1.43 ± 0.06 ^a	0.035	0.55	1106 ^d	296	
Mező-Madaras	L3.7	Fall		3.3	3.5	5.2 ± 1.2	0.88	0.72	2.89 ± 0.17 ^a	0.021	2.37	982 ^d	296	
McKinney	L4	Find		3.5	3.6	4.7 ± 0.8	1.14	0.97	3.32 ± 0.13 ^a	0.021	2.83	843 ^d	296	
McKinney*	L4	Find		3.5	3.6	4.7 ± 0.8	1.10	0.95	3.60 ± 0.09 ^a	0.021	3.10	943 ^d	296	
Beenham	L5	Find		3.3	3.6	9.8 ± 0.7	0.73	0.43	1.83 ± 0.04 ^a	0.028	1.08	761 ^d	296	
Bluff	L5	Find	W2	3.2	3.7	12.3 ± 0.9	1.12	0.70	3.20 ± 0.08 ^a	0.032	1.98	885 ^d	296	
Bluff*	L5	Find	W2	3.2	3.7	12.3 ± 0.9	1.10	0.68	3.17 ± 0.07 ^a	0.032	1.96	895 ^d	296	
Taiban	L5	Find		3.3	3.7	8.7 ± 0.9	1.14	0.83	3.19 ± 0.09 ^a	0.026	2.32	839 ^d	296	
Taiban*	L5	Find		3.3	3.7	8.7 ± 0.9	1.07	0.79	3.31 ± 0.12 ^a	0.026	2.42	921 ^d	296	
Tsarev	L5	Find		3.3	3.6	8.8 ± 0.9	1.05	0.77	3.32 ± 0.17 ^a	0.026	2.42	963 ^d	296	
Tsarev*	L5	Find		3.3	3.6	8.8 ± 0.9	1.15	0.84	3.29 ± 0.12 ^a	0.026	2.39	872 ^d	296	
Ausson	L5	Fall		3.2	3.8	15.1 ± 1.1	0.58	0.22	1.56 ± 0.04 ^a	0.036	0.60	834 ^d	296	
Sevrukovo	L5	Fall		3.4	3.8	8.9 ± 1.2	0.99	0.69	2.90 ± 0.08 ^a	0.026	2.04	857 ^d	296	
Neenach	L6	Find		3.3	3.9	14.5 ± 1.1	0.82	0.38	2.18 ± 0.06 ^a	0.035	1.02	798 ^d	296	

Meteorite	Class	Fall	Weathering grade**	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Thermal diffusivity (mm ² /s)	Corrected thermal diffusivity (1.33 x 10 ⁻⁴ Pa) (mm ² /s)	Thermal conductivity (W/m/K)	Aspect ratio of pores	Corrected thermal conductivity (1.33 x 10 ⁻⁴ Pa) (W/m/K)	Specific heat capacity (J/kgK)	Temp. (K)	Notes
Neenach*	L6	Find		3.3	3.9	14.5 ± 1.1	0.79	0.37	2.14 ± 0.08 ^a	0.035	0.99	808 ^d	296	
Valkeala	L6	Find		3.4	3.4	2.4 ± 0.1	1.03	0.94	2.98 ± 0.11 ^a	0.018	2.73	861 ^d	296	
Valkeala*	L6	Find		3.4	3.4	2.4 ± 0.1	0.95	0.87	3.15 ± 0.05 ^a	0.018	2.90	985 ^d	296	
Alfianello ¹	L6	Fall		3.2	3.6	9.9 ± 0.9	0.61	0.31	1.21 ± 0.02 ^a	0.028	0.62	610 ^d	296	
Alfianello* ¹	L6	Fall		3.2	3.6	9.9 ± 0.9	0.58	0.29	1.15 ± 0.04 ^a	0.028	0.58	617 ^d	296	
Bath Furnace	L6	Fall		3.4	3.8	10.9 ± 1.1	0.87	0.51	2.19 ± 0.41 ^a	0.029	1.28	745 ^d	296	
Bath Furnace*	L6	Fall		3.4	3.8	10.9 ± 1.1	0.79	0.48	2.46 ± 0.14 ^a	0.029	1.49	919 ^d	296	
Richfield	LL3.7	Find		3.4			0.85		2.87 ± 0.11 ^a			1000 ^d	296	
Richfield*	LL3.7	Find		3.4			0.69		2.89 ± 0.08 ^a			1250 ^d	296	
Arcadia 1	LL6	Find		3.1	3.4	9.0 ± 0.9	0.72	0.48	2.36 ± 0.20 ^a	0.027	1.55	1043 ^d	296	
Arcadia 2	LL6	Find		3.1	3.6	12.6 ± 1.1	0.72	0.38	2.18 ± 0.09 ^a	0.032	1.14	955 ^d	296	
Lake Labyrinth	LL6	Find		3.2			0.37		1.63 ± 0.16 ^a			1397 ^d	296	
Lake Labyrinth*	LL6	Find		3.2			0.47		1.64 ± 0.08 ^a			1096 ^d	296	
Dhurmsala	LL6	Fall		3.3	3.7	11.6 ± 1.1	0.79	0.43	1.96 ± 0.03 ^a	0.030	1.05	754 ^d	296	
Dhurmsala*	LL6	Fall		3.3	3.7	11.6 ± 1.1	0.75	0.39	1.87 ± 0.11 ^a	0.030	0.98	759 ^d	296	
Jelica	LL6	Fall		3.1	3.7	16.5 ± 1.1	0.16	0.05	1.19 ± 0.02 ^a	0.039	0.35	2388 ^d	296	
Bondoc	Mesosiderite-B4	Find		3.2	3.6	10.0 ± 0.9	0.76		3.01 ± 0.30 ^a			1219 ^d	296	
Bondoc*	Mesosiderite-B4	Find		3.2	3.6	10.0 ± 0.9	0.82		2.73 ± 0.56 ^a			1031 ^d	296	
Bendegó	Iron, IC	Find		7.5	8.1	7.6 ± 2.0			12.93 ± 0.46 ^a				296	
Bella Roca	Iron, III AB	Find		7.8	8.2	5.0 ± 2.7			10.97 ± 0.18 ^a				296	
Canyon City	Iron, III AB	Find		7.4	8.2	8.8 ± 2.3			10.44 ± 0.14 ^a				296	
Szurgot et al. (2014)														
NWA 4560	LL3.2	Find					0.8		4.6 ± 0.10				200	4
NWA 4560	LL3.2	Find					0.9		4.10 ± 1.3				300	4
Wach et al. (2014)														
Kilabo	LL6	Fall							4.9 ± 1.10				200	5
Kilabo	LL6	Fall							4.5 ± 1.10			690	300	5
Opeil et al. (2012)														
Pillistfer	EL6	Fall		3.6	3.7	2.4			5.51 ± 0.01 ^b				200	6
Pultusk	H5	Fall		3.4	3.7	7.5			1.25 ± 0.01 ^b				200	6
Barbotan	H5	Fall		3.5	3.8	6.9			3.05 ± 0.01 ^b				200	6
Collescipoli	H5	Fall		3.5		9.1			0.82 ± 0.01 ^b				200	1, 6
La Ciénega	H6	Find							1.90 ± 0.01 ^b				200	6
Holbrook 1	L/LL6	Fall		3.2	3.6	10.4			0.45 ± 0.01 ^b				200	6
Holbrook 2	L/LL6	Fall		3.2	3.6	10.4			1.15 ± 0.01 ^b				200	6
Bath Furnace 3	L6	Fall		3.5	3.7	4.3			3.15 ± 0.01 ^b				200	6
Bath Furnace 2	L6	Fall		3.5	3.7	4.3			2.72 ± 0.01 ^b				200	6
Bath Furnace 1	L6	Fall		3.5	3.7	4.3			2.26 ± 0.01 ^b				200	6
Frankfort	Howardite	Fall		2.9	3.3	12.7			1.31 ± 0.01 ^b				200	6
Frankfort	Howardite	Fall		2.9	3.3	12.7			1.60 ± 0.01 ^b				300	6
Los Angeles	Shergottite	Find		2.8	3.1	8.1			0.77 ± 0.01 ^b				200	6
Los Angeles	Shergottite	Find		2.8	3.1	8.1			0.90 ± 0.01 ^b				300	6
Szurgot et al. (2012)														

Meteorite	Class	Fall	Weathering grade**	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Thermal diffusivity (mm ² /s)	Corrected thermal diffusivity (1.33 x 10 ⁻⁴ Pa) (mm ² /s)	Thermal conductivity (W/m/K)	Aspect ratio of pores	Corrected thermal conductivity (1.33 x 10 ⁻⁴ Pa) (W/m/K)	Specific heat capacity (J/kgK)	Temp. (K)	Notes
Soltmany	L6	Fall					1.50		3.90 ± 0.20 ^c				300	7
Soltmany	L6	Fall					1.80		4.50 ± 0.30 ^c				300	7
Soltmany	L6	Fall							4.70 ± 0.30 ^c				200	7
Soltmany	L6	Fall							5.10 ± 0.30 ^c				200	7
Szurgot (2011)														
NWA 4039	Eucrite	Find					0.41		1.10 ± 0.10 ^c				300	8
HaH 286	Eucrite	Find					0.93		1.90 ± 0.01 ^c				300	8
Allende	CV3	Fall		2.9	3.7	21.9	0.56		1.40 ± 0.10 ^c			874 ^d	300	2, 8
DaG 610	H4	Find					1.64		2.50 ± 0.20 ^c				300	8
Gold Basin	L4	Find	W2-3	3.4	3.5	3.0	1.32		3.70 ± 0.20 ^c			824 ^d	300	2, 8
El Hammami	H5	Find		3.4	3.8	10.2	1.57		4.50 ± 0.30 ^c			843 ^d	300	2, 8
Vaca Muerta	Mesosiderite-A1	Find		3.1	3.1	1.2	1.34		2.50 ± 0.20 ^c			600 ^d	300	2, 8
Brahin	Pallasite PMG	Find					2.1		5.40 ± 0.30 ^c				300	8
Brahin	Pallasite PMG	Find					6.9		16.50 ± 0.90 ^c				300	8
Odessa	IAB-MG	Find		7.1			12.4		45 ± 3 ^c			508 ^d	300	2, 8
Campo del Cielo	IAB-MG	Find					15.8		52 ± 3 ^c				300	8
Gibeon	IVA	Find					7.2		23 ± 1 ^c				300	8
Gibeon	IVA	Find							25 ± 2 ^c				300	8
Opeil et al. (2010)														
Abee	EH6	Fall		3.5	3.6	3.0			5.35 ± 0.01 ^b			500	200	9
Cronstad	H5	Fall							1.88 ± 0.01 ^b			550	200	9
Lumpkin	L6	Fall		3.7					1.47 ± 0.01 ^b			570	200	1, 9
NWA 5515	CK4	Find		2.7					1.48 ± 0.01 ^b			500	200	3, 9
Cold Bokkeveld	CM2	Fall		2.4	2.8	15.0			0.50 ± 0.01 ^b			500	200	9
Campo del Cielo	IAB-MG	Find							22.40 ± 0.01 ^b			375	200	9
Beech et al. (2009)														
Gao-Guenie	H5	Fall							2.99 ± 0.15 ^c			732	300	10
Szurgot et al. (2008)														
Morasko	IAB-MG	Find							25 ± 1			478	293	11
Morasko	IAB-MG	Find							50 ± 2				301	11
Morasko	IAB-MG	Find							35 ± 2				301	11
Morasko	IAB-MG	Find							39 ± 2				301	11
Morasko	IAB-MG	Find							51 ± 2				301	11
Morasko	IAB-MG	Find							67 ± 2				301	11
Yomogida and Matsui (1983)														
ALHA77288	H6	Find	C	3.7	3.8	2.0	1.75		3.53			547 ^d	200	12
ALHA77288	H6	Find	C	3.7	3.8	2.0	1.11		2.96			723 ^d	300	12
ALHA77294	H5	Find	Ae	3.4	3.8	12.9	0.41		0.75			551 ^d	200	12
ALHA77294	H5	Find	Ae	3.4	3.8	12.9	0.26		0.63			721 ^d	300	12
Gilgoin	H5	Find		3.6	3.8	5.0	1.82		3.6			548 ^d	200	12
Gilgoin	H5	Find		3.6	3.8	5.0	1.34		3.49			721 ^d	300	12
Gladstone	H4	Find		3.6	3.7	5.0	1.10		2.16			552 ^d	200	12
Gladstone	H4	Find		3.6	3.7	5.0	0.89		2.28			720 ^d	300	12

Meteorite	Class	Fall	Weathering grade**	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Thermal diffusivity (mm ² /s)	Corrected thermal diffusivity (1.33 x 10 ⁻⁴ Pa) (mm ² /s)	Thermal conductivity (W/m/K)	Aspect ratio of pores	Corrected thermal conductivity (1.33 x 10 ⁻⁴ Pa) (W/m/K)	Specific heat capacity (J/kgK)	Temp. (K)	Notes
Monroe	H4	Fall		3.6	3.8	5.9	1.20		2.35			547 ^d	200	12
Monroe	H4	Fall		3.6	3.8	5.9	0.87		2.26			726 ^d	300	12
Wellman	H5	Find		3.6	3.8	6.1	1.96		3.85			549 ^d	200	12
Wellman	H5	Find		3.6	3.8	6.1	1.37		3.54			722 ^d	300	12
Y-74156	H4	Find		3.6	3.9	9.2	0.81		1.54			529 ^d	200	12
Y-74156	H4	Find		3.6	3.9	9.2	0.62		1.55			698 ^d	300	12
Y-74647	H4.5	Find		3.5	3.8	9.1	0.60		1.15			546 ^d	200	12
Y-74647	H4.5	Find		3.5	3.8	9.1	0.46		1.15			724 ^d	300	12
ALHA76009	L6	Find	B	2.9	3.6	19.4	0.34		0.55			565 ^d	200	12
ALHA76009	L6	Find	B	2.9	3.6	19.4	0.27		0.58			754 ^d	300	12
ALHA77231	L6	Find	A/Be	3.1	3.6	14.3	0.64		1.2			610 ^d	200	12
ALHA77231	L6	Find	A/Be	3.1	3.6	14.3	0.49		1.13			759 ^d	300	12
ALHA78103	L6	Find	B	3.2	3.7	13.4	0.40		0.73			569 ^d	200	12
ALHA78103	L6	Find	B	3.2	3.7	13.4	0.28		0.69			760 ^d	300	12
ALHA78251	L6	Find	B	3.2	3.7	13.2	0.47		0.85			566 ^d	200	12
ALHA78251	L6	Find	B	3.2	3.7	13.2	0.29		0.72			761 ^d	300	12
Arapahoe	L5	Find		3.5	3.6	2.5	1.15		2.31			571 ^d	200	12
Arapahoe	L5	Find		3.5	3.6	2.5	1.00		2.55			728 ^d	300	12
Bruderheim	L6	Fall		3.3	3.6	8.0	0.55		1.03			567 ^d	200	12
Bruderheim	L6	Fall		3.3	3.6	8.0	0.39		0.98			759 ^d	300	12
Farmington	L5	Fall		3.4	3.6	5.5	1.11		2.14			567 ^d	200	12
Farmington	L5	Fall		3.4	3.6	5.5	0.95		2.44			758 ^d	300	12
Kunashak	L6	Fall		3.4	3.6	5.2	0.96		1.86			569 ^d	200	12
Kunashak	L6	Fall		3.4	3.6	5.2	0.77		1.98			759 ^d	300	12
Leedey, A	L6	Fall		3.3	3.6	10.4	0.22		0.4			567 ^d	200	12
Leedey, A	L6	Fall		3.3	3.6	10.4	0.17		0.42			751 ^d	300	12
Leedey, B	L6	Fall		3.2	3.6	10.6	0.25		0.47			573 ^d	200	12
Leedey, B	L6	Fall		3.2	3.6	10.6	0.20		0.49			756 ^d	300	12
META78003	L6	Find	B	3.3	3.6	7.8	0.82		1.54			567 ^d	200	12
META78003	L6	Find	B	3.3	3.6	7.8	0.63		1.58			758 ^d	300	12
New Concord	L6	Fall		3.3	3.6	9.2	0.42		0.78			568 ^d	200	12
New Concord	L6	Fall		3.3	3.6	9.2	0.31		0.76			760 ^d	300	12
Y-74191	L3.7	Find	A	3.2	3.6	10.3	0.68		1.24			569 ^d	200	12
Y-74191	L3.7	Find	A	3.2	3.6	10.3	0.54		1.32			760 ^d	300	12
Y-75097	L6	Find	A	3.3	3.7	10.3	0.52		0.97			569 ^d	200	12
Y-75097	L6	Find	A	3.3	3.7	10.3	0.39		0.96			758 ^d	300	12
Matsui and Osako (1979)														
Y-74191	L3.7	Find	A						0.67			603	300	13
Butler and Jenkins (1963)														
Canyon Diablo	IAB-MG	Find							63			548	293	14
Wood (1963)														
Norton County	Aubrite	Fall							1.51				NA	15
Orlovka	H5	Find							1.76				NA	15

Meteorite	Class	Fall	Weathering grade**	Bulk density (g/cm ³)	Grain density (g/cm ³)	Porosity (%)	Thermal diffusivity (mm ² /s)	Corrected thermal diffusivity (1.33 x 10 ⁻⁴ Pa) (mm ² /s)	Thermal conductivity (W/m/K)	Aspect ratio of pores	Corrected thermal conductivity (1.33 x 10 ⁻⁴ Pa) (W/m/K)	Specific heat capacity (J/kgK)	Temp. (K)	Notes
Zvonkov	H6	Find							2.43				NA	15
Krymka	LL3.2	Fall							1.76			695	NA	15

Notes: NWA = Northwest Africa; ALH = Allan Hills; Y = Yamato; MET = Meteorite Hills, Hah = Hammadah al Hamra, DaG = Dar al Gani.

* Measured in orthogonal direction.

** Weathering grade from the Catalogue of meteorites (Grady 2000).

¹ Fusion crust present on the measurement surface.

^a Standard deviation/mean.

^b Opeil et al. (2012) do not list error, but state, "error is generally on the order of 0.01 W/m/K".

^c Calculated from listed error of instrument used (Ostrowski and Bryson 2019).

^d Specific heat capacity is calculated from thermal conductivity, thermal diffusivity and bulk density.

1. Data from Britt and Consolmagno (2003).
2. Data from Macke (2010); average of all samples measured.
3. Data from Macke (2010); sample from Vatican collection.
4. Data from Szurgot et al. (2014).
5. Data from Wach et al. (2014).
6. Data from Opeil et al. (2012).
7. Data from Szurgot et al. (2012).
8. Data from Szurgot (2011).
9. Data from Opeil et al. (2010).
10. Data from Beech et al. (2009).
11. Data from Szurgot et al. (2008).
12. Data from Yomogida and Matsui (1983). Grain density is calculated from reported bulk density and porosity.
13. Data from Matsui and Osako (1979).
14. Data from Butler and Jenkins (1963).
15. Data from Wood (1963).

Table III. Class average and standard deviation of chondrites in Table 1. Number of the samples is given in parentheses. Conductivities represent data at 300 K and vacuum pressure.

	All	Falls	Finds
H chondrites			
This study			
Average conductivity (W/m/K)	1.85 ± 0.11 (21)	-	1.85 ± 0.11 (21)
Average porosity (%)	11.2 ± 1.1 (12)	-	11.2 ± 1.1 (12)
All data*			
Average conductivity (W/m/K)	1.93 ± 0.10 (34)	1.85 ± 0.04 (5)	1.95 ± 0.11 (29)
Average porosity (%)	9.3 (24)	7.35 (4)	9.7 (20)
L chondrites			
This study			
Average conductivity (W/m/K)	1.86 ± 0.10 (20)	1.28 ± 0.13 (7)	2.16 ± 0.09 (13)
Average porosity (%)	9.3 ± 0.9 (12)	10.0 ± 1.0 (5)	8.7 ± 0.8 (7)
All data*			
Average conductivity (W/m/K)	1.64 ± 0.12 (39)	1.51 ± 0.14 (17)	1.74 ± 0.10 (22)
Average porosity (%)	9.2 (28)	8.6 (12)	9.7 (16)
LL chondrites			
This study			
Average conductivity (W/m/K)	1.02 ± 0.10 (5)	0.80 ± 0.06 (3)	1.35 ± 0.12 (6)
Average porosity (%)	12.4 ± 0.7 (4)	14.1 ± 1.1 (2)	10.8 ± 0.8 (2)
All data*			
Average conductivity (W/m/K)	1.02 ± 0.10 (5)	0.80 ± 0.06 (3)	1.35 ± 0.12 (2)
Average porosity (%)	12.4 ± 0.7 (4)	14.1 ± 1.1 (2)	10.8 ± 0.8 (2)
L/LL chondrites			
This study			
Average conductivity (W/m/K)	0.56 ± 0.06 (2)	0.056 ± 0.06 (2)	-
Average porosity (%)	14.3 ± 0.6 (1)	14.3 ± 0.6 (1)	-
All data*			
Average conductivity (W/m/K)	0.68 ± 0.04 (4)	0.68 ± 0.04 (4)	-
Average porosity (%)	12.4 (2)	12.4 (2)	-
C chondrites			
This study			
Average conductivity (W/m/K)	0.77 ± 0.03 (3)	0.77 ± 0.03 (3)	-
Average porosity (%)	14.6 ± 0.6 (2)	14.6 ± 0.6 (2)	-
All data*			
Average conductivity (W/m/K)	0.86 ± 0.04 (5)	0.70 ± 0.04 (4)	1.48 ± 0.01 (1)
Average porosity (%)	16.5 (4)	16.5 (4)	-
E chondrites			
This study			
Average conductivity (W/m/K)	0.63 ± 0.09 (1)	0.63 ± 0.09 (1)	-
Average porosity (%)	22.6 ± 1.4 (1)	22.6 ± 1.4 (1)	-
All data*			
Average conductivity (W/m/K)	3.83 ± 0.04 (3)	3.83 ± 0.04 (3)	-
Average porosity (%)	9.3 (3)	9.3 (3)	-

* Includes the results in this study and literature data in Table 1.

Note: Average thermal conductivities are calculated from results at low pressures of this study, Opeil et al. (2010, 2012), Yomogida and Matsui (1983) and Matsui and Osako (1979).

Fig. 1. Relationship between the aspect ratio of pores and porosity.

Fig. 2. Thermal conductivities (300 K) and porosities of the results in this study combined with literature data. Average thermal conductivities are calculated from results at low pressures of this study, Opeil et al. (2010, 2012), Yomogida and Matsui (1983) and Matsui and Osako (1979). The number above each bar is the number of the samples.

Fig. 3. Thermal conductivities (300 K and vacuum conditions) of ordinary chondrite classes in this study including falls and finds. Boxes are bounded by the third and first quartile and median divides the bar. The lower quartile is the median of the lower half of the data and the upper quartile is the median of the upper half of the data. Bars display the error and extend to the maximum and minimum. Both inner data points and outlier points are shown. The cross is the mean marker.

Fig. 4. Thermal conductivities (vacuum conditions) of ordinary chondrite classes in the compiled data in Table 2. Boxes are bounded by the third and first quartile and median divides the bar. The lower quartile is the median of the lower half of the data and the upper quartile is the median of the upper half of the data. Bars display the error and extend to the maximum and minimum. Both inner data points and outlier points are shown. The cross is the mean marker.

Fig. 5. Relationship between thermal conductivity (low pressure) and porosity of chondrite falls. R -squared values of 0.88 and 0.61 represent data in this study and all data, respectively. Chondrites Abee, Alfianello, and Pillistfer are not included in the correlations.

Fig. 6. Relationship between thermal conductivity (low pressure) and bulk density of chondrite falls in the compiled database. R -squared values of 0.64 and 0.62 represent data in this study and all data, respectively. Chondrites Abee, Alfianello, Pillistfer, and Cold Bokkeveld are not included in the correlations.

Fig. 7. Relationship between thermal diffusivity and porosity of chondrite falls in the compiled database. R -squared values of 0.85 and 0.70 represent data in this study and all data, respectively. Chondrites Abee and Alfianello are not included in the correlations.

Fig. 8. Thermal conductivities for model compositions of H, L, and LL chondrites under vacuum (1.33×10^{-4} Pa).

Fig. 9. Thermal conductivities for model compositions of H, L, and LL chondrites at 1 atm.

Fig. 10. Thermal conductivity in ambient air of different theoretical compositions of meteorites.