The specific heat capacity of asteroidal regolith material – A review

TherMoPS III Workshop, Budapest February 2019

Jens Biele, Max Hamm, Matthias Grott (DLR)

Key points

- „Cologne cp database“, a literature review of measurments of 70 end-member minerals, from low-T (~5K) to melting point or decomposition with typically 1% accuracy

- Includes Cp measurements at low T of ices, tholin analogues, minerals, etc. relevant for TNOs

- Lunar cp raw data points fitted with synthetic curve with temperature 5-1400K

- Analysis for asteroid analogue planned using a DSC (differential scanning calorimeter,) in the lab, temperature range ca. 93-1023K,

Motivation

- Knowledge or an estimate of $c_P(T)$ is required to extract, e.g., k from thermal inertia

- Around 300K, the temperature dependence of c_P is a second-order effect in "thermal inertia" and not strongly dependent on the material (besides the mass fraction of metallic FeNi).

- At low temperatures, c_P is very strongly temperature and composition dependent. The surfaces of outer solar system objects (icy moons, TNOs) are at such low temperatures that the specific heat capacities can be dramatically different from that of silicates at room temperature.

Motivation II

- Lunar cp(T) is available only for 90-350K but lunar minerals differ from CC minerals
- Available interpolation polynomials diverge beyond narrow T limits
- Few meteoritic cp-curves have been determined, mostly only mean value at 175K (Consolmagno, et al. 2013)

Cp data of extraterrestrial matter

- Only a handful of meteorite heat capacities have been published, with T ≥ 300 K or at a ~175 K (Consolmagno et al., 2013).
- Macke et al., 2016 measured the heat capacity over the range 5-350 K for 6 individual meteorite specimens using the Quantum Design PPMS system. Their publication show the data from 75 to 300K. The low-temperature data exist (Macke, priv. comm. 31.03.2018), but they are not published yet
- The only other extraterrestrial material with known c_P over a limited temperature range is 9 lunar samples from the Apollo missions, and many studies have used these values as a “standard” $c_P(T)$ curve.
- Heat capacity is, however, strongly dependent also on composition, thus the use of lunar data for, e.g., C- or M-class asteroids or objects containing frozen volatiles may give rise to large systematic errors.

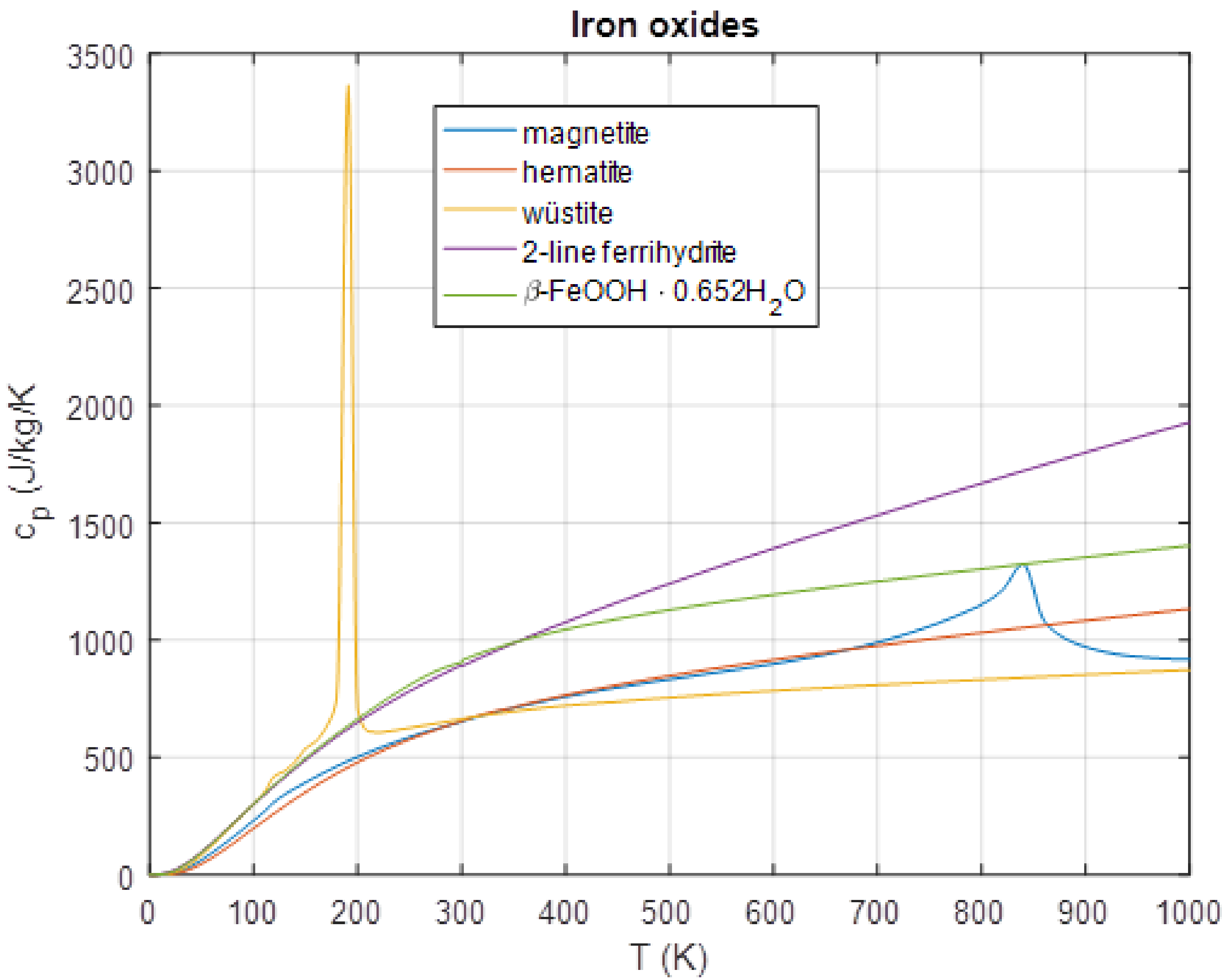
Method

- cp(T) of many minerals can be found int the literature, both for low and high temperatures is well and accurately known
- Review of the cp(T) for endmember minerals over as wide as possible T ranges, studies in literature, often either <300K or >300K.
- Review of available data (meteorites, lunar, incl. compositions)
- Review of typical mineralogical compositions of lunar samples, H, L, LL, metal, various types of CC meteorites
- Fitting of data to linear combination of mineral cp(T) ➔ permits extrapolation to low and high T
- Construction of physically reasonable correlation equations or tables apt for easy interpolation

Excess cp

- For a mechanical mixture, $c_{P,mix} = \sum_i X_i c_{P,i}, \quad \sum X_i = 1$
- But some important minerals (olivine, feldspars, pyroxenes) form solid solutions
- Their cp is not strictly given by the mechanical mixture equations, but the “excess cp” is negligible for high temperatures and only sometimes relevant at T<100K
- We use the measured cp for olivines (2 components); model for feldspars and pyroxenes (3,4 endmembers) in preparation

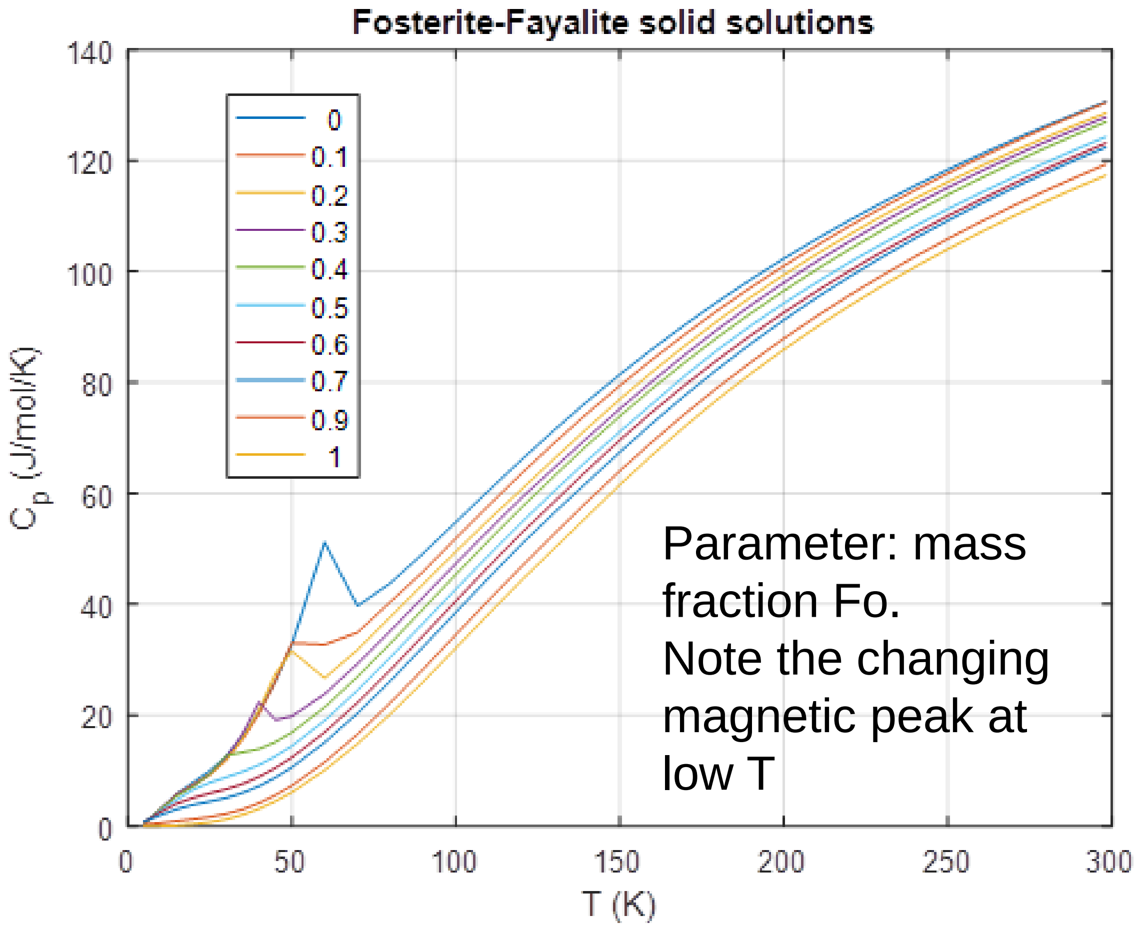
Transition peaks - examples



Olivine is not a end-member mineral..

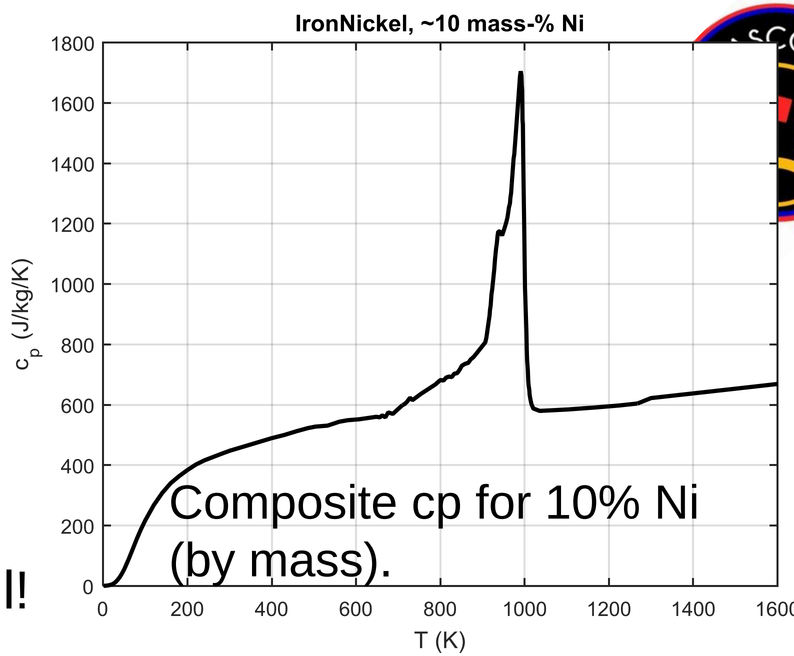
.. but a solid solution of Forsterite (Fo) and Fayalite (Fa).

Also, “Basalt” is not a end-member mineral, but a rock with widely varying composition and cp!



Parameter: mass fraction Fo.
Note the changing magnetic peak at low T

A few points..

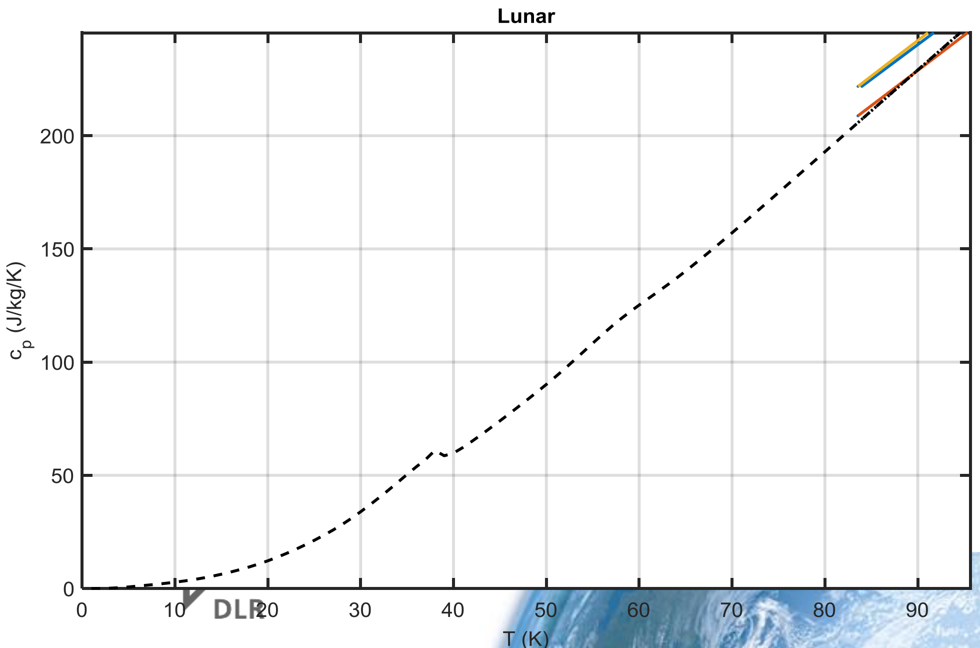


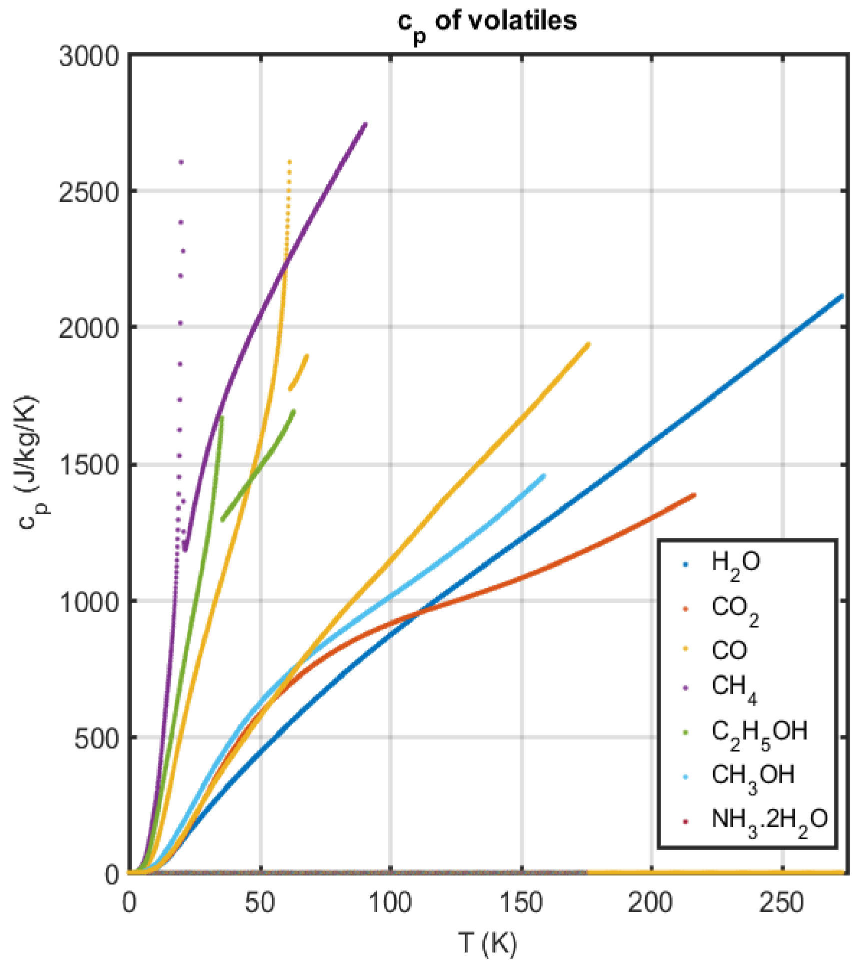
- CC and OC have similar cp
- Carbon content cp variation is small!
- But FeNi fraction significantly decreases cp

- It is worth noting that if Γ is the observable, the product of density ρ and heat capacity c_p usually is the quantity of interest. As silicates, coal, and FeNi have very different densities of 3000, 1350 and 8000 kg/m³, respectively, the same mass fraction of FeNi has a much larger impact on Γ than carbon.

Outer solar system – ices etc.

Silicates have very low cp at low temperatures, but solar systems ices not!
TI of "bedrock" at 30K is ~200 tiu for silicates but up to 2000 tiu for ices!





Lunar materials cp

- Most lunar samples are mare material, i.e. basaltic, with a few samples from highland material, which is mostly anorthosite (mineral: anorthite $CaAl_2Si_2O_8$). Mare basalts are further distinguished as “Low-Ti”, 1.5-9% of TiO_2, and “high-Ti”, >9% TiO_2

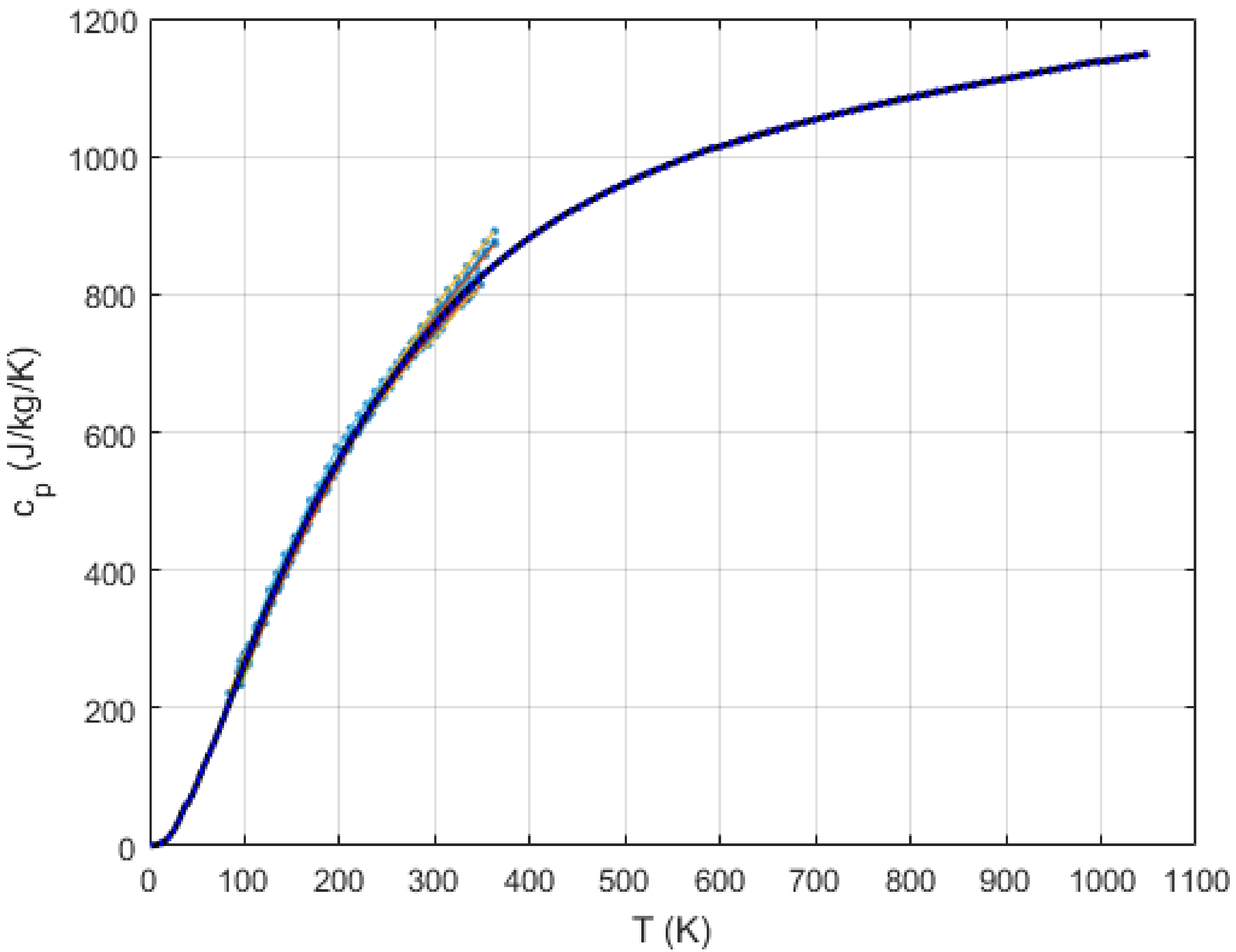
- Lunar regolith contains about 0.3±0.15 mass-% of “native iron”, i.e. elemental iron-nickel metal with typically 5.7% Ni, the rest is iron

- Silicate minerals make up 80-90 vol-%

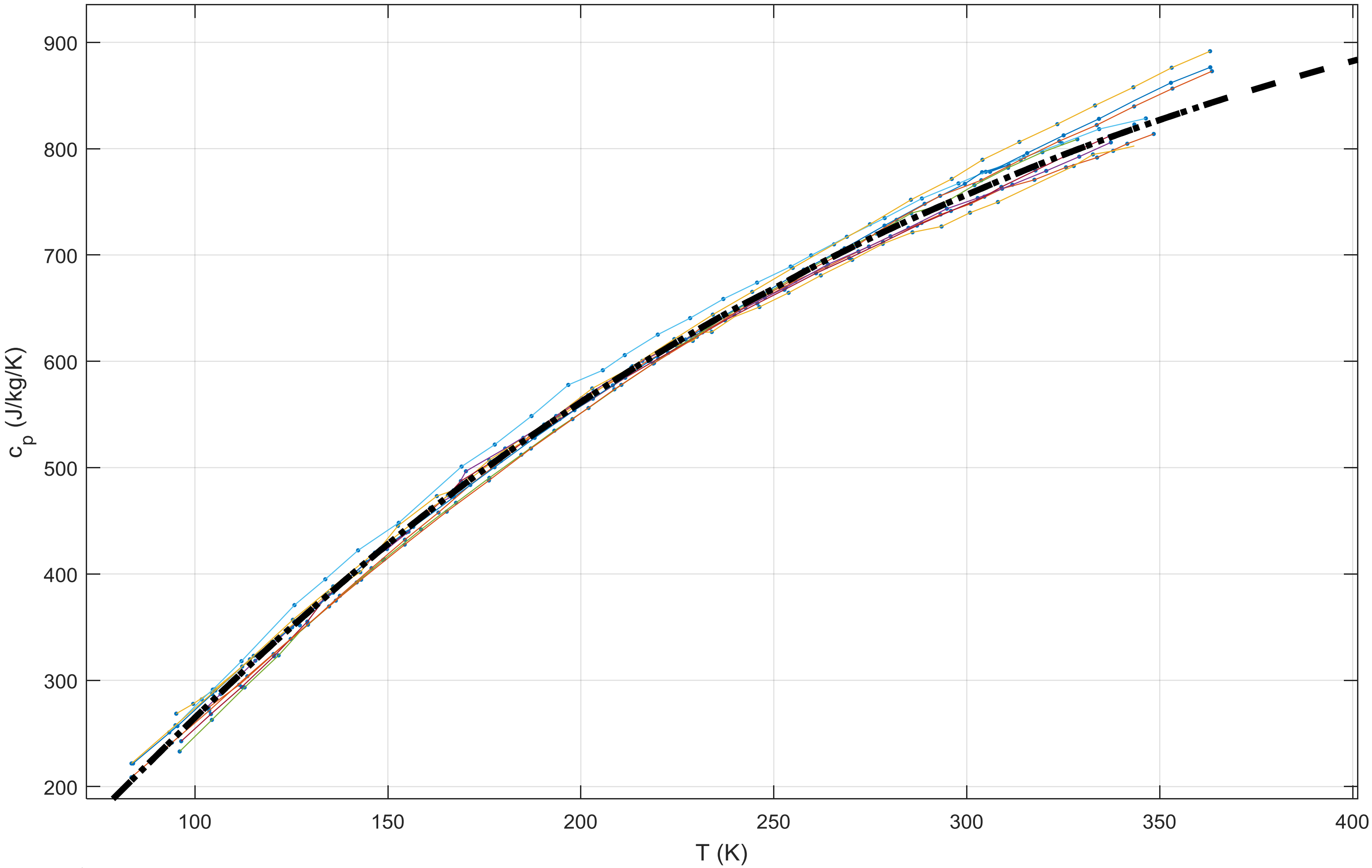
- Only 9 lunar samples have been measured for cp over the range ~100K to ~360K

New: Lunar average cp

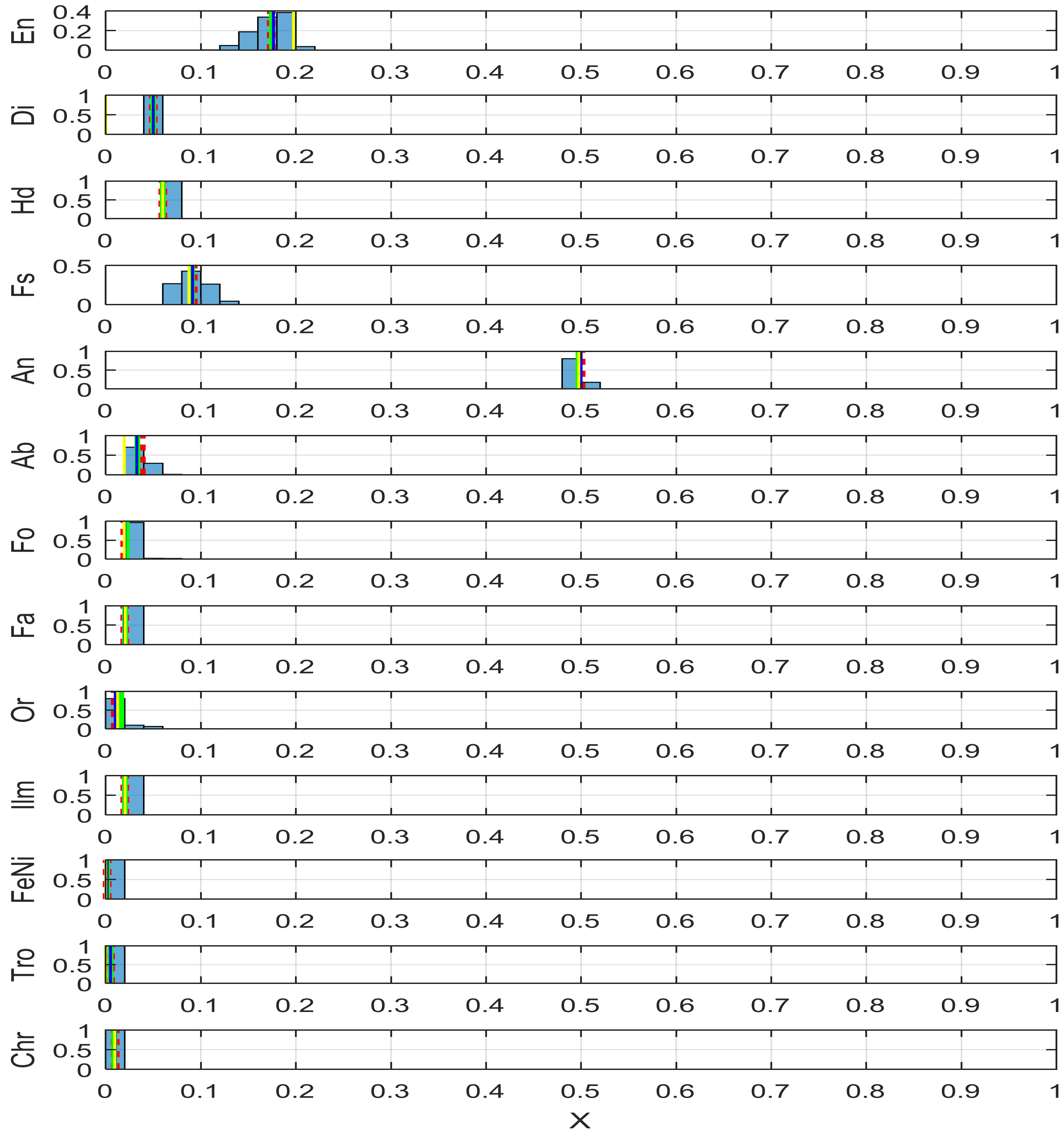
All raw data points with fitted and extrapolated cp (combination of lunar minerals)



New: Lunar average cp



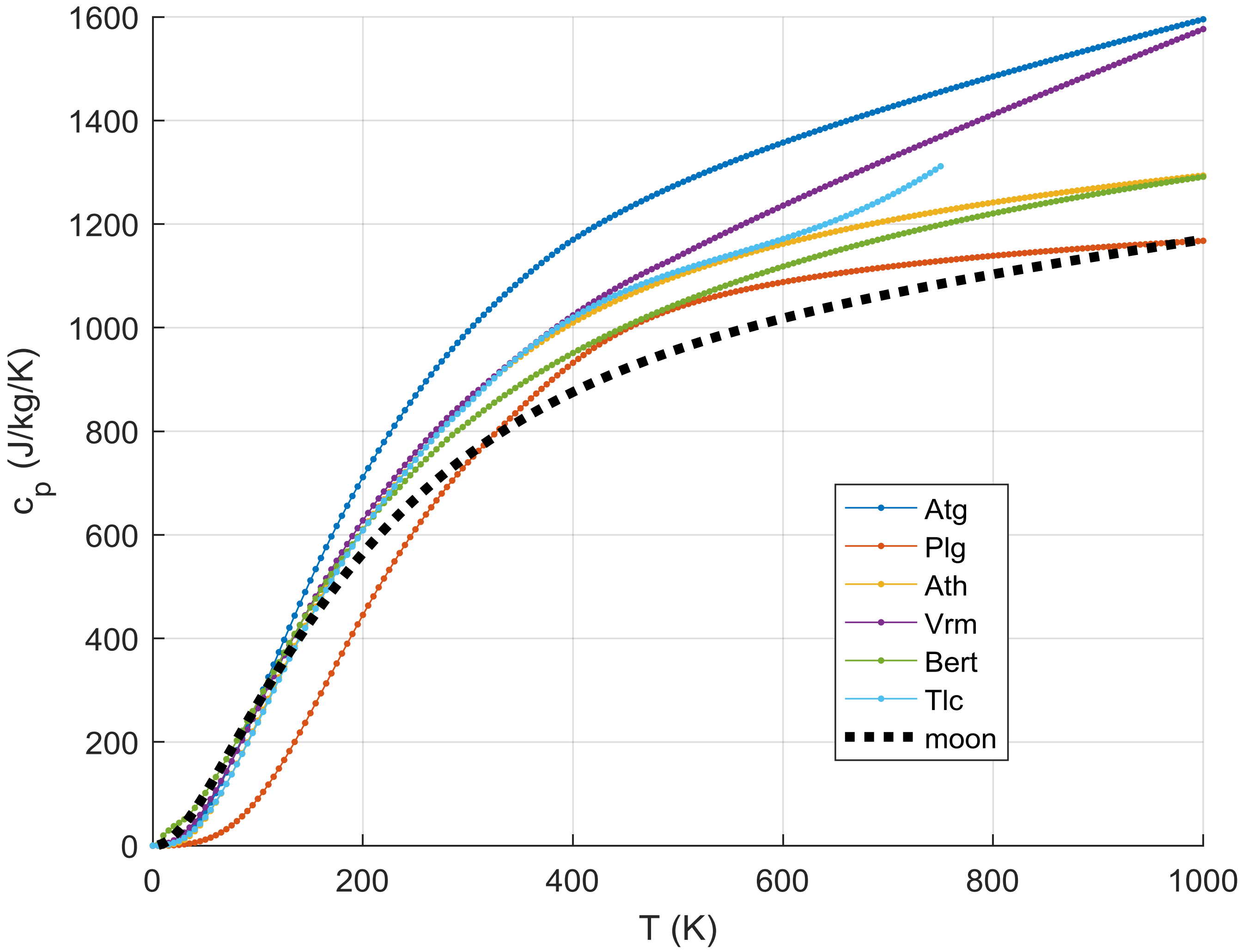
New


En
0.4
0.2
0
Di
Hd
Fs
An
Ab
Fo
Fa
Or
Ilm
FeNi
Tro
Chr
1
0.5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
x

Cp of phyllosilicates

- We further calculated model $c_P(T)$ curves for a number of typical meteorite classes with known mineralogical compositions and for some laboratory regolith analogues.

Cp of phyllosilicates, compared to average lunar cp

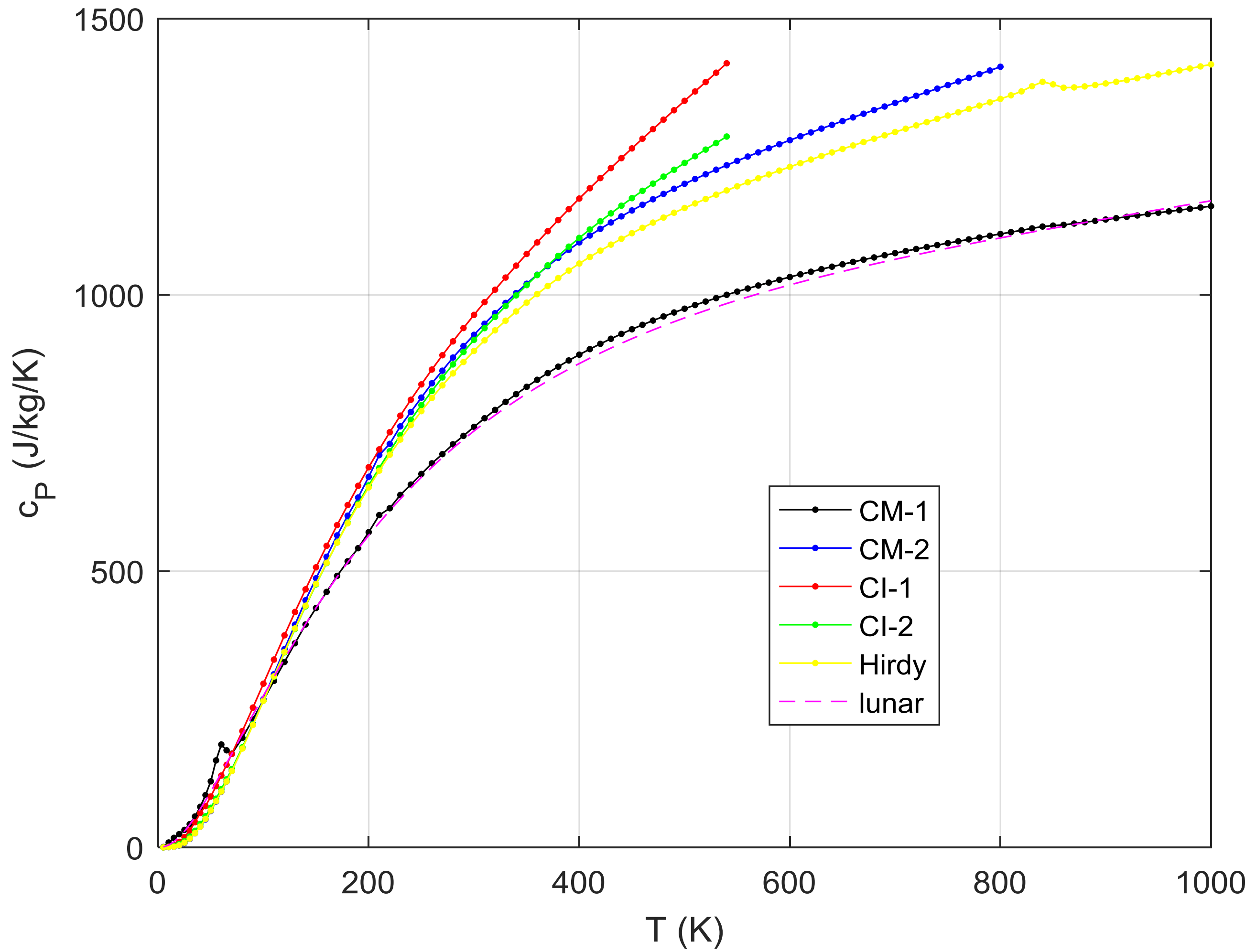


Minerals and their mass fractions X assumed for the cp(T) of DI regolith simulants.

CM-1 mineral, X		**CM-2 mineral, X**		**CI-1 mineral, X**		**CI-2 mineral, X**		**Hirdy (Phobos) mineral, X**	
Fa	0.5700	Atg	0.7000	Atg	0.3650	Atg	0.4800	Atg	0.6250
Atg	0.2200	Mag	0.1000	Eps	0.1500	Eps	0.0600	Mag	0.0790
Fo	0.0729	Fo	0.0675	Mag	0.1150	Mag	0.1350	Py	0.0940
Fa	0.0081	Fa	0.0075	Plg	0.0900	Plg	0.0500	Fo	0.0684
Coal	0.0350	Coal	0.0350	Fo	0.0630	Fo	0.0630	Fa	0.0076
Py	0.0250	Py	0.0250	Fa	0.0070	Fa	0.0070	Cal	0.0460
En	0.0150	En	0.0150	Py	0.0600	Py	0.0650	Dol	0.0470
Fs	0.0050	Fs	0.0050	Vrm	0.0500	Vrm	0.0900	Coal	0.0330
Mag	0.0100	Sms	0.0350	Sd	0.0400	Coal	0.0500		
Dol	0.0100	Sd	0.0100	Coal	0.0350				
Sms	0.0290			Gp	0.0250				
sum	**1**		**1**		**1**		**1**		**1**

Calculated cp of analogue materials

- "Hirdy" denotes UTF TB, the U Tokyo Phobos simulant, Tagish Lake Variant [by Hideaki Miyamoto and Takafumi Niihara (University of Tokyo)]



Work summary

- Review of the specific heat capacities of the most abundant endmember minerals (including iron-nickel metal) and organic materials found in meteorites and the c_P of frozen volatiles thought to exist on outer solar system bodies
- Built up a computerized database to calculate the c_P of any of ~70 minerals and compounds for any temperature between absolute zero and close to melting (or decomposition) temperatures.
- Missing thermophysical data for a solid be calculated from the contributions of the constituent minerals if the mineralogical composition of a rock is known, i.e the mass fractions X_i of the constituents
- Test method with lunar c_P-data and extrapolate the lunar data to very low and very high temperatures with confidence.
- Calculated model $c_P(T)$ curves meteorite classes with known mineralogical compositions and for some laboratory regolith analogues.

Thank you for your attention!