Betrothed Coordination Number and Porosity, No More

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Background

Thermal conductivity of Ryugu and Bennu reveal **unusually low thermal inertias**, widely interpreted as **high boulder microporosity** [1-4]. However, heat flow in granular materials is governed by both **porosity (ϕ)**, which describes the volume fraction of voids, and the **coordination number (Z)**, the average number of contacts per particle. Since different formation and evolutionary histories can produce aggregates with identical porosities but widely different particle connectivity or vice versa [5], **interpreting thermal inertial as a pure function of porosity is inherently degenerate**.

Objective

Using a random ballistic deposition with rolling (RBDR) algorithm developed by [6] **to decouple (Z, ϕ)-parameter space**, we quantify how **thermal conductivity depends jointly on packing density and particle connectivity. We measure the uncertainty this degeneracy** introduces to asteroid porosity estimates derived from thermal measurements.

Particle Aggregates and Heat Transport

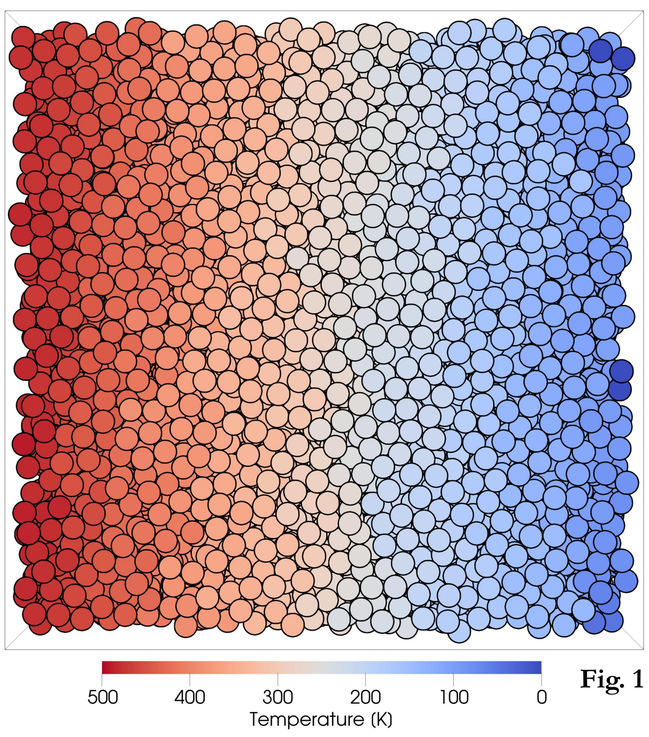

Fig. 1

We model C-type asteroid boulders as **monodisperse assemblies** of spheres. Using RBDR algorithm [6], we generated aggregates with decoupled porosity ϕ and coordination number Z. To isolate the structural effects on contact-dominated heat flow, the **contact conductance are held constant**. Thermal evolution is carried out in LIGGGHTS® DEM [7] until equilibrium. Bulk thermal conductivity is subsequently determined using Fourier's law as **published in [8]**.

Decoupled Power-Law Relation

By normalizing effective bulk conductivity by the characteristic constant scale, we isolate the effect of structural geometry into a dimensionless function $F(Z, \phi)$.

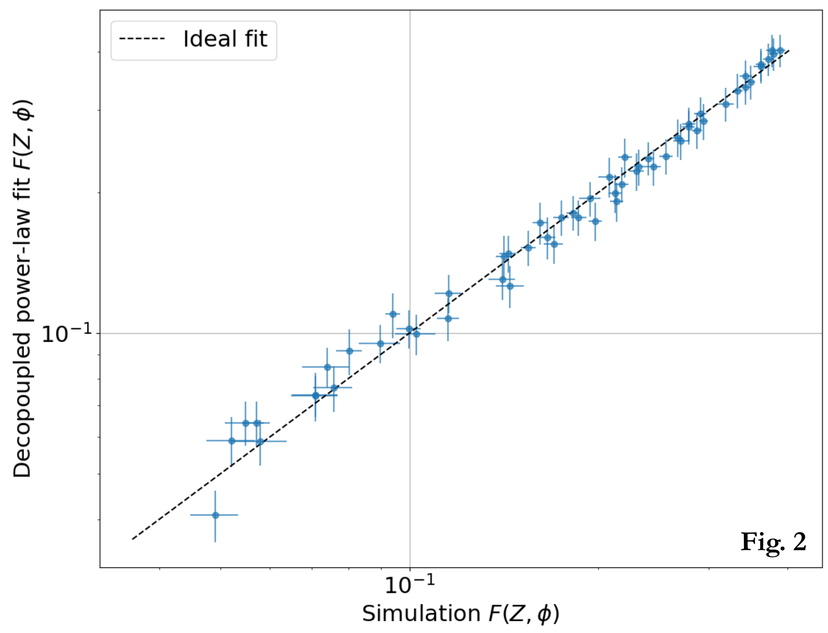

Fig. 2

We observed the following decoupled power-law relation

$$F(Z, \phi) = A \cdot (Z - Z_c)^{\alpha} \cdot (1 - \phi)^{\beta}$$

for $Z > Z_c$. Here, $Z_c = 2$, is the critical coordination number below which the contact network fails to form continuous contact network. The least-square best fit parameters are $A = 0.60 \pm 0.04$, $\alpha = 0.71 \pm 0.02$, $\beta = 1.34 \pm 0.07$. Figure 2 shows the quality against an ideal fit.

Decoupling Coordination Number and Porosity

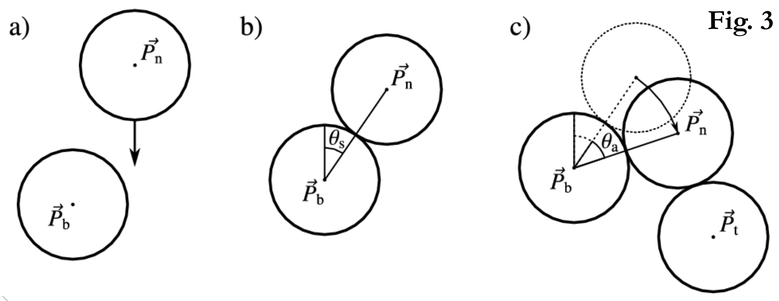

Fig. 3

- RBDR by [6] drops spherical particles towards a plane from random positions
- New particle $\vec{P}_n$ *rolls* along the existing particle $\vec{P}_b$ by additional angle θ_{max} (see Figure 3)
- Rolling *attempted* for N_φ azimuthal angles
- Using RBDR we produce aggregates of randomly placed sphere with $0.50 \lesssim \phi \lesssim 0.87$ and $2 \lesssim Z \lesssim 4$.

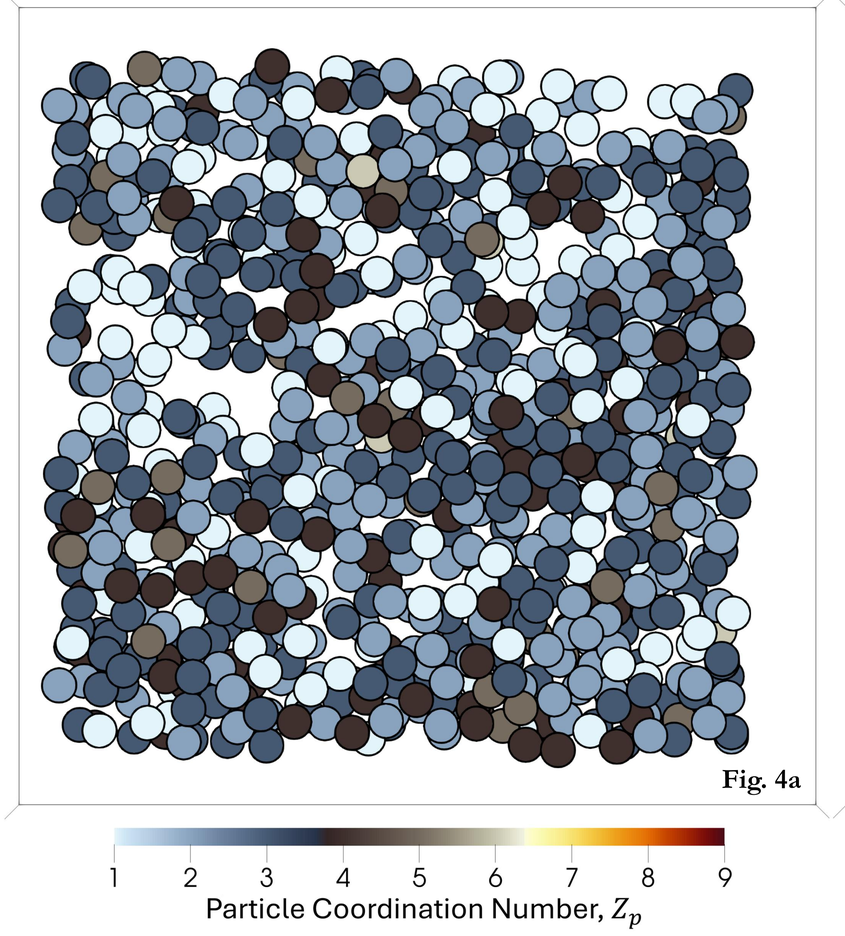

Fig. 4a

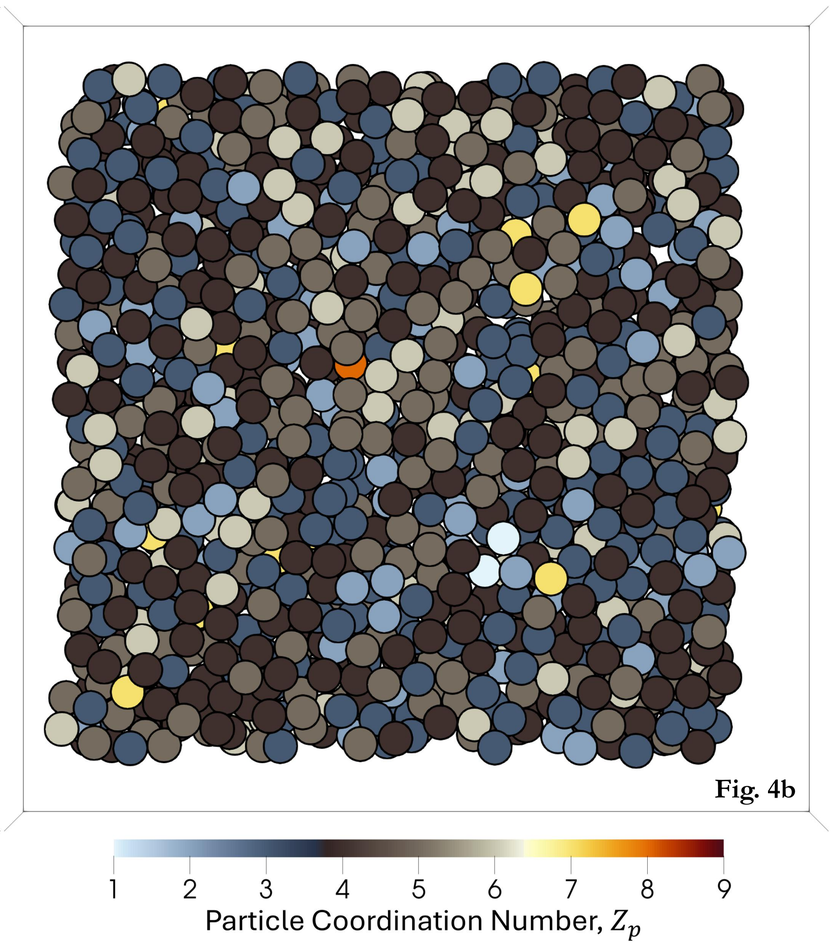

Fig. 4b

Figure 4 shows cross-sectional layers through two different particle aggregates generated using RBDR. The layer in panel 4a is from a highly porous aggregate with average coordination number $Z = 2.51$ and porosity $\phi = 0.67$, and that in 4b is from a tightly packed aggregates with $Z = 4.05$ and porosity $\phi = 0.49$. The colors in each panel represent the coordination number of individual particles.

Thermal conductivity w.r.t. Coordination Number and Porosity

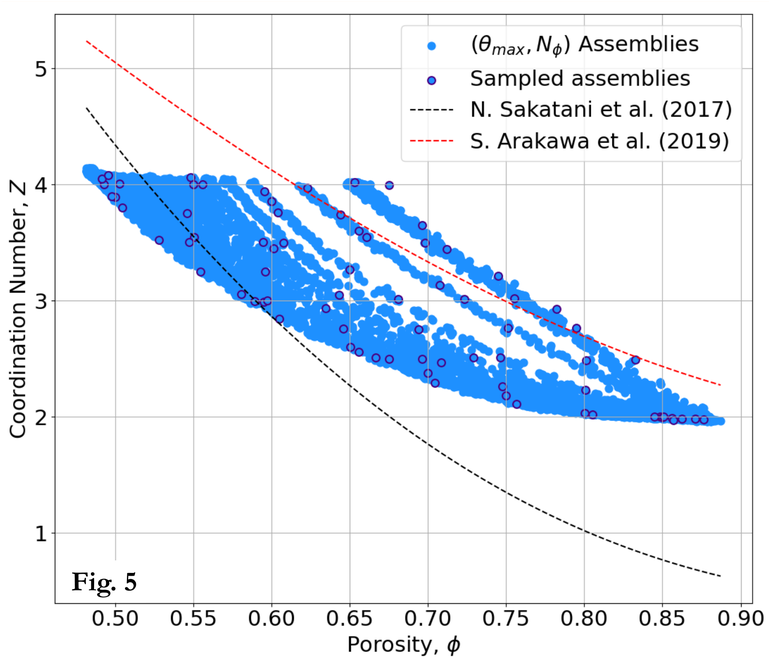

Fig. 5

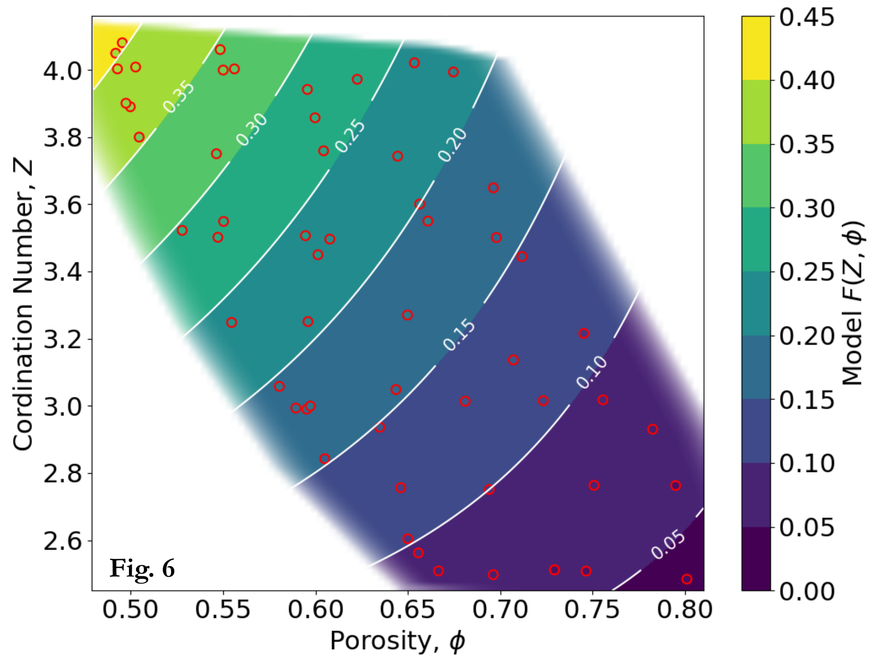

Fig. 6

Figure 5 shows the (Z, ϕ)-parameter space, indicating the assemblies produced using RBDR in blue dots. The aggregates sampled for thermal simulations are highlighted here with purple circles. The parameter space sampled by [9] (dashed black) and [10] (dashed red) are shown for reference. Figure 6 shows the contours of dimensionless conductivity $F(Z, \phi)$ with respect to coordination number Z and porosity ϕ. The white lines are the constant conductivity isolines, and the color bar indicates the weighted least-square best fit to simulation data. The red circles represent the particle assemblies in thermal equilibrium used for fitting.

Key Results

- **High Structural Degeneracy**
  Aggregates with identical porosities can differ in coordination number by $\Delta Z \sim 1.5$. Conversely, aggregates with the exact same particle connectivity can span a porosity range of $\Delta\phi \sim 0.17$
- **Conductivity Variations**
  Model captures conductivity variations up to a **factor of 3** at fixed porosity $(\phi = 0.70)$, and a **factor of 2** at a constant coordination number $(Z = 3.0)$
- **Inherent Measurement Uncertainty**
  Due to the structural degeneracy, estimating boulder porosity from thermal measurements introduces relative uncertainties up to $\Delta\phi/\phi \sim 17\%$

Conclusion, Caveat, Continuation…

- **Bottom Line**
  Bulk thermal conductivity of asteroid boulders cannot be expressed as a function of porosity alone; **microstructural connectivity must be explicitly included** for comprehensive interpretation of thermal measurements
- **Regime of Impact**
  Boulder porosities observed on Ryugu and Bennu (30-50%) showcase minimal structural degeneracy. However, it **becomes important between 60% and 70% porosity**, the regime corresponding to pristine, uncompacted primordial material [1]
- **Future Work**
  Include polydispersity, irregular grains, and sintering-driven contact evolution

References

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