ASTEROIDS COMETS METEORS
6-10 VII 2026 Poznań

Betrothed Coordination Number and Porosity, No More

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Thermal conductivity of asteroid regolith and boulders strongly influences surface evolution, thermal inertia, as well as orbital dynamics [4, 9, 2, 3]. We study solid heat transport in asteroid boulders, represented here as assemblies of spherical particles, where bulk conductivity is dominated by particle-particle heat transfer. It depends directly on contact conductance and two microstructural parameters: coordination number Z, the average number of contacts per particle, and the porosity ϕ, the fraction of void space within the boulders. Existing models, however, typically treat bulk conductivity as a function of ϕ alone, implying a one-to-one relationship between packing density and heat transport [10, 5, 14, 1]. Such an approach neglects the independent role of Z, that can vary significantly at fixed porosity depending on the formation and compaction history of the material.

We employ a modified random ballistic deposition with rolling (RBDR) algorithm [11] to generate monodisperse granular assemblies, that allows us to independently vary Z and ϕ across a wide parameter space. This spans porosities $0.50 \lesssim \phi \lesssim 0.87$ and coordination number $2 \lesssim Z \lesssim 4$, without conflating their effects. Thermal simulations are then performed numerically on select assemblies using a DEM software LIGGGHTS [12]. By maintaining a constant contact conductance, we isolate structural contributions to heat transport thereby quantifying and disentangling the roles of packing density and particle-particle connectivity.

Our results reveal that effective thermal conductivity follows a decoupled power-law relation $F(Z, \phi)$ with a threshold coordination number $Z_c = 2$, that marks the percolation transition below which no continous solid conduction pathways exist. The model captures variation up to a factor of three in conductivity at fixed porosity ($\phi = 0.70$) and up to a factor of two at constant coordination number ($Z = 3.0$).

These findings have direct implications for interpreting asteroid thermal measurements. Missions to Ryugu and Bennu indicate the presence of fine-grained boulders with elevated porosities relative to chondritic material [6, 8, 13, 7]. This places them in the parameter regime where a single-valued porosity-conductivity mapping becomes least reliable. Our decoupled power-law relation shows that granular aggregates with similar thermal conductivities differ in relative porosity by as much as $\Delta\phi/\phi \approx 17\%$. This structural degeneracy introduces a non-trivial uncertainity in porosity estimates derived from the thermal measurements and needs to be taken into account.

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