

## Thermophysical Analysis of Regolith on (101955) Bennu: The Coarse Regolith Conundrum

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### Abstract:

Thermophysical analyses of planetary bodies such as the Moon, Mars, and numerous asteroids have allowed for remote estimates of regolith physical properties, such as particle size and packing density, as well as the relative spatial abundance of boulders. Here we define “regolith” as a particulate assemblage where most particles are comparable to or smaller than the length scale of the diurnal skin depth (the e-folding depth of the diurnal thermal wave).

Until recently, regolith and boulders were believed to be thermally quite distinct; regolith on the Moon, Mars, and most asteroids was usually known or suspected to be fine (i.e., ranging from fine dust to sand), meaning that it was known or assumed to have a thermal inertia much lower than that of boulders and bedrock. Upon the arrival of NASA OSIRIS-REx at asteroid Bennu and JAXA Hayabusa2 at asteroid Ryugu and the subsequent thermophysical analyses of the respective asteroid surfaces, this preconceived notion of thermophysically distinct regolith and boulders/bedrock was found to be flawed (DellaGiustina and Emery et al., 2019; Sugita et al., 2019). Boulders cover the vast majority of both asteroids' surfaces, yet the thermal inertia values determined for these boulder-rich surfaces fall within a range that was previously believed to exclusively represent coarse, sand-to-pebble-sized regolith. Recent work has been devoted to the analysis of the boulders' thermal inertia and the physical interpretation thereof (Grott et al., 2019; Rozitis et al., in revision); the general conclusion so far is that the boulders have very low thermal conductivity and density owing to the presence of numerous pores and fractures, more so than most (or perhaps all) carbonaceous chondrite meteorites in Earth's collections. As such, these boulders are likely to be structurally distinct from all known meteorite specimens.

Although fine-particulate regolith is rare on the surface of Bennu, it is present in some locations. It is still of great interest to probe the physical properties of this regolith by means of thermal analysis so as to make predictions about the properties of the samples that will be returned by OSIRIS-REx and to learn about the evolution of the asteroid surface and the mechanisms by which regolith is produced and lost or destroyed. There remains the enigmatic

question: although we suspect that the boulders on Bennu are distinct from the meteorite collection, will the returned samples of particulate material share these distinct properties? At what scales can we define the physical thermally relevant properties of boulders and regolith particles on Bennu? In other words, if the boulders are indeed highly fractured and porous, are the regolith particles also fractured and porous or are their dimensions below the relevant length scales?

It is very challenging to estimate the physical properties of the regolith on Bennu using thermal data, even in regions where it appears to be abundant, due to the coarseness of the regolith. Commonly used planetary thermophysical models rely on the assumption that the material on the surface, be it regolith or rock, can be approximated as a continuous, non-discretized material with physical properties that are either constant with depth or are allowed to vary with depth in some well-defined way (e.g. an exponential density increase, or up to a few layers of physically distinct material, such as regolith on bedrock or dust coatings). This assumption of material continuity is valid when regolith particles are smaller, or perhaps even *much* smaller, than the diurnal skin depth of the thermal wave. However, high-resolution images of the Nightingale Crater on Bennu, which is the OSIRIS-REx mission's primary sample collection site, revealed a particle size frequency distribution (SFD) that crosses this threshold; i.e., there are particles present that are smaller than, comparable to, *and* larger than the diurnal skin depth (~1–5 cm) present within a single, meters-wide observation footprint. The thermophysical behavior of such a regolith configuration has never been comprehensively studied and likely cannot be properly approximated with standard 1D thermal modeling methods.

We will present preliminary results using a 3D regolith model where we render hundreds of regolith particles and rocks, approximated as spheres, in a finite element mesh framework. The model is heated diurnally with a solar source to study the thermal response of such skin depth–crossing SFDs under Bennu surface-like conditions. The SFD of the particles is informed by particle size counts in Nightingale Crater from high-resolution visible images. With the SFD partially constrained, we are able to focus our efforts on exploring the material property parameter space, namely to estimate the thermal conductivity and density of individual regolith particles. Given the coarseness of the regolith on Bennu, we find that the model is more sensitive than one might expect to the thermal conductivity of the individual regolith particles owing to the effects of particle non-isothermality (Ryan et al., 2020). Although this present modeling work is focused on analyzing thermal emission data of Bennu obtained by the OSIRIS-REx Thermal Emission Spectrometer (OTES, Christensen et al., 2018), we aim to expand our efforts to study the more general thermal behavior of coarse regoliths and regoliths with wide SFDs under a range of solar heating conditions.

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#### References:

Christensen, P.R. et al. (2018). The OSIRIS-REx Thermal Emission Spectrometer (OTES) Instrument. *Space Science Reviews* 214, 87.

DellaGiustina, D.N., Emery, J.P., et al. (2019) Properties of rubble-pile asteroid (101955) Bennu from OSIRIS-REx imaging and thermal analysis, *Nature Astronomy*, DOI:10.1038/s41550-019-0731-1.

Grott, M., Knollenberg, J., et al. (2019) Low thermal conductivity boulder with high porosity identified on C-type asteroid (162173) Ryugu, *Nature Astronomy*, DOI:10.1038/s41550-019-0832-x.

Rozitis, B., Ryan, A.J., Emery, J.P., et al. (in revision) Asteroid (101955) Bennu's Weak Boulders and Thermally Anomalous Equator, *Science Advances*, submitted March 2020.

Ryan, A., Pino Muñoz, D., Bernacki, M., Delbo, M. (2020) Full-Field Modeling of Heat Transfer in Asteroid Regolith: Radiative Thermal Conductivity of Polydisperse Particulates, *JGR:Planets*. DOI:10.1029/2019JE006100.

Sugita, S., Honda, R., et al. (2019) The geomorphology, color, and thermal properties of Ryugu: Implications for parent-body processes, *Science*. DOI:10.1126/science.aaw0422