MACHINE LEARNING–BASED THERMOPHYSICAL ANALYSIS OF OSIRIS-REX SAMPLE SITE CANDIDATES. S. Cambioni[1], M. Delbo[2], J. D. P. Deshapriya[3], G. Poggiali[4], A. Ryan[1], J. P. Emery[5], V. E. Hamilton[6], P. R. Christensen[7], and D. S. Lauretta[1]. [1]University of Arizona, Tucson AZ 85721 (cambioni@lpl.arizona.edu); [2]Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lab. Lagrange, Nice Cedex 06304, France; [3]LESIA, Observatoire de Paris, PSL Research University, CNRS, Meudon Principal Cedex 92195, France; [4]University of Florence, Department of Physics and Astronomy, Sesto Fiorentino (Florence), Italy / INAF-Osservatorio Astrofisico di Arcetri, Florence, Italy; [5]Northern Arizona University, Flagstaff AZ, USA; [6]Southwest Research Institute, Boulder CO, USA; [7]Arizona State University, Tempe AZ, USA.

Overview. We use a new methodology [1] that combines machine learning and Bayesian statistics to constrain the surface properties of the OSIRIS-REx final four site candidates from measurements of the emitted infrared radiance. Our approach consists of: (1) training a neural network representation of the thermophysical behavior of the surface; and, (2) using the trained network as forward model in a Bayesian inversion of the observed infrared radiance. Terrains are modeled as composed by two units: rocks and fine particles (also called fines, with average particle size smaller than 2 cm). The surface properties of the sites – surface roughness, thermal inertia of the fines and rock units, and relative abundance – are retrieved; the contributions from the fine particle and rock units are well separated. The sites differ in the thermal inertia of the rock component, relative abundance of the units and surface roughness. Conversely, the thermal inertia of the fines is found to be remarkably similar from site to site (equal to about 150 $Js^{-1/2}K^{-1}m^{-2}$), suggesting a preferential size for the fine particles on the surface.

Introduction. The surfaces of airless planetary bodies are typically covered in regolith, a layer of fragmented and unconsolidated material that typically derives from the break-down of rocks and boulders on the surface of the asteroid. Large (hundreds of km diameter) asteroids are generally found to show more mature (finer) regolith than smaller asteroids [2]. The images obtained by NASA's OSIRIS-REx mission at asteroid (101955) Bennu [3] and JAXA's Hayabusa2 at asteroid (162173) Ryugu [4] seem to confirm this trend, as the target asteroids are covered in very coarse regolith, with predominance of boulders.

The rough morphology of small asteroids offers multiple challenges to near-surface, landing, and sampling operations of active space missions. NASA's OSIRIS-REx mission will collect a sample of the surface of Bennu and return it to Earth for laboratory analysis [3]. The sampling device of OSIRIS-REx, TAGSAM, is designed to collect and return at least 60g of the regolith, provided particles are smaller than about 2 cm in diameter. Accurate estimates of the availability of fine particles on the asteroid, including average particle size and abundance, are thus key to define the sampleability of the surface.

OTES data. The thermal and mechanical environment of the surface poses constraints on sampling operations. The thermal emission informs about the thermophysical properties of the surface. The OSIRIS-REx Thermal Emission Spectrometer is currently measuring infrared radiances emitted by the surface of the asteroid in the spectral range 5.71-100 µm (1750-100 cm^{-1}) with a spectral sample interval of 8.66 cm^{-1} [5]. Under the hypothesis that the infrared radiance is contributed by the thermal emission of both fine particles and rocks, we use the methodology in [1] to estimate the thermal inertia of the fine particle and rock components, relative abundance of the units, and the surface roughness. The abundance of rocks and surface roughness inform us about the hazard associated with sampling a certain region. The thermal inertia of the fines can be converted in average particle size. As a guideline, particles on Bennu with thermal inertia less than 280 $Js^{-1/2}K^{-1}m^{-2}$ are predicted to have average size smaller than 2 cm in diameter, according to the model by [6].

Methodology. Our approach consists of approximating the thermophysical function y = F(x) (x: surface properties; y: infrared radiance) using neural networks trained on a dataset of thermal simulations of the type: {surface properties; infrared radiance}. The dataset has been generated using the TPM model [7] following the procedure described in [1]. Once trained, the networks can predict the infrared radiance at highly reduced computational time with respect to the "parent" model (running in less than a second versus minutes on a single processor 2.8 GHz Intel Core i7), thus enabling Markov Chain Monte Carlo (MCMC) Bayesian inference of surface properties from observed infrared radiances. MCMC requires thousands of runs of the forward model to sample the unknown posterior distributions – thus the need for a fast and accurate predictor, i.e., a trained neural network. We follow a two-step approach. We first fit the data with a single-component model (a neural network predicting the infrared radiance corresponding to the average thermal inertia and roughness). We then employ the trained 2-component model in the Bayesian inversion of the infrared radiance. In this case, the MCMC scheme is informed of the result of

the single-component fit, in order to guide the inversion towards convergence. For a more detailed explanation of the methodology, we refer the reader to [1].

Results. We focus on the analysis of the OTES data concerning the final four site candidates, which have been down-selected from a longer list of sites according to spacecraft safety (e.g. avoidance of high slopes and large boulders) and science criteria. For sites Nightingale, Osprey, and Kingfisher, we find that the goodness-of-fit (reduced χ^2) of the 2-component model is more than 3-σ better than that obtained by using the 1-component model. This means that the data are better fit if the thermal emission is modeled as contributed by two materials – which are here assumed to be fine particles (with size less than 2 cm in diameter) and rocks. The thermal emission from site Sandpiper is instead better fit using a 1-component model. The results of the Bayesian inversion using the 2-component model, in terms of the posterior probability distribution of the surface properties, are in Figure 1.

Discussion. The site candidates are distinguishable in terms of their thermophysical properties. The surface roughness (in terms of Hapke angle [8]) changes from site to site. The unit consistent with fine particles is present at every site, and it is the most abundant at the Osprey site (>50% at the scale of the diurnal skin depth). However, Osprey also shows the roughest surface. While the most probable thermal inertia of the rock component is different from site to site (but always below 600 $Js^{-1/2}K^{-1}m^{-2}$, bottom-left panel of Figure 1), the thermal inertia of the fine particles is found to be remarkably similar, with a most probable value of about 150 $Js^{-1/2}K^{-1}m^{-2}$ (top-right panel of Figure 1). Such value of thermal inertia is consistent with a particle size of about 3.6 mm – 5.3 mm for Cold Bokkeveld–like meteorite, or 9.5 mm – 1.5 cm assuming very low density and thermal conductivity (1400 kg/m^3 and 0.08 W/mK respectively, perhaps consistent with the values for the boulder on Ryugu analyzed by the MARA instrument [9]).

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References: [1] Cambioni S. et al (2019a) *Icarus*, 325, 16-30. [2] Delbo M. et al. (2007) *Icarus,* 190, 236-249. [3] Lauretta D.S. et al (2017), *Space Sci Rev.,* 212, 925-984. [4] Abe M (2012) *Asteroids, Comets, Meteors*, Vol. 1667. [5] Christensen P. R. et al. (2018) *Space Sci. Rev.,* 214, id87. [6] Sakatani N. et al. (2018) *Icarus,* 309, 13-24. [7] Delbo M. et al. (2015) *Asteroids IV*: 107-128. [8] Hapke B. (1984) *Icarus,* 59(1), 41-59. [9] Grott M. et al. (2019) *Nature Astronomy*, 1-6.

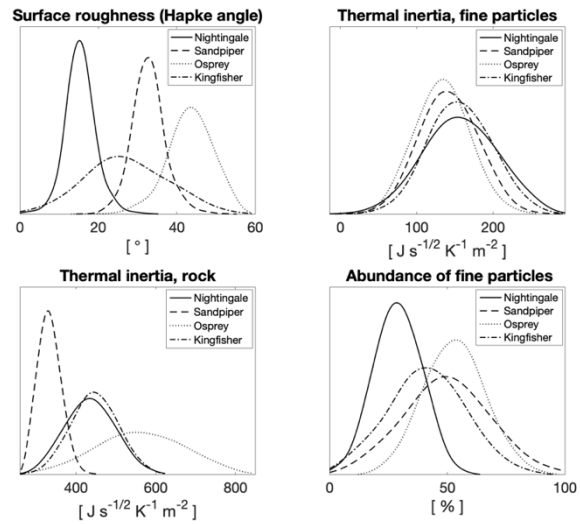

Figure 1. Posterior probability distributions of the thermophysical properties of four sample site candidates on the surface of asteroid (101955) Bennu. The properties – surface roughness, thermal inertia of fine particles and rocks, and relative abundance of the units – are estimated by means of Bayesian inversion of infrared radiances collected by the OTES instrument. Among the sites, "Osprey" is found to have the highest abundance of material with thermal inertia lower than 280 $Js^{-1/2}K^{-1}m^{-2}$ which, following the method by [6], is here interpreted as fine particles with size less than 2 cm. The sites also differ in their roughness and thermal inertia of the rock component. Furthermore, the thermal inertia of the fine particles is remarkably similar among the different sites, which could indicate a preferential size for the particle material (see text).