QUANTIFYING ASTEROID REGOLITH POROSITY FROM RADAR DATA. D.C. Hickson[1], A.L. Boivin[2], C. Tsai[3], M.G. Daly[1], R.R. Ghent[2,4] [1]Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada (hicksodc@yorku.ca), [2]Solar System Exploration Group, Department of Earth Sciences, University of Toronto, Toronto, Ontario, Canada, [3]Department of Physics, University of Toronto, Toronto, Ontario, Canada, [4]Planetary Science Institute, Tucson, Arizona, USA.

Introduction: The structures of asteroids from their surfaces to their interiors are relatively unknown, and provide insight into the formation and evolution of asteroids. These bodies represent some of the most primitive material in our solar system, and understanding their formation and evolutions can help decipher the mysteries of the early solar nebula. In the last few decades, several asteroids have been targeted by robotic space exploration missions, revealing diverse properties and collecting valuable ground-truth observations. The current *Hayabusa2* and *OSIRIS-REx* missions by JAXA and NASA respectively aim at thoroughly analyzing two C-complex asteroids and returning pristine regolith samples, procuring excellent data on the surface properties of the asteroids. Spacecraft missions have confirmed the presence of fine grained regolith covering most asteroid surfaces, which is also inferred from thermophysical models and radar data. Attempts have been made at quantifying the density of the near-surface regolith on asteroid surfaces from radar observations, making use of the correlation between material permittivity and density observed in laboratory experiments [1,2,3]. In this work, we expand on our previous research efforts in this area [4] by validating the use of particular permittivity models with high precision permittivity measurements of seven geologic samples. These models are then used to calculate the porosity in the near-surface (within the radar penetration depth) of several asteroids with well-known bulk properties.

Methods: The radar reflectivity of a material is largely determined by the complex permittivity of that material (for non-magnetic, non-conducting materials) where the real part of the permittivity represents the electrical energy stored, and the imaginary part represents the dissipation of energy. The relative (to vacuum) complex permittivity of seven geologic powder samples was measured for a range of powder bulk densities using the transmission line method and equipment outlined in [5], and the silica aerogel density variation technique introduced in [4]. The samples span silicate, carbonate, oxide, and phyllosilicate mineralogies, and were chosen for their relevance to carbonaceous chondrite compositions and their well-studied permittivity. Characterization of the grain density, grain size, and chemical composition was completed for each sample. An average for the zero-porosity (i.e, the density of the individual mineral grains that comprises the powdered sample) real part of the permittivity for each sample was derived from the literature. With this value and the known permittivity of air (~1), any models attempting to fit the measurements of the real part of the permittivity for each powder sample are bounded by the permittivity of each phase of the mixture: air (at 100% porosity), and the zero-porosity mineral grains (at 0% porosity). A detailed review of electromagnetic mixing equations was carried out to define their intrinsic limitations and assumptions. Several common mixing models were then fitted to our experimental data using non-linear least squares regression.

Results: From this analysis, it is observed that the Looyenga-Landau-Lifshitz (LLL) and Bruggeman Symmetric (BG) models are the most accurate in predicting the change in the permittivity of a (non-magnetic, non-conducting) geologic sample with that sample's porosity. Using these theories to extrapolate our measurements to zero-porosity values, we observe a linear correlation of the zero-porosity real part of the permittivity with the sample grain density. This relationship has been identified in similar studies of solid rock samples [6]. The zero-porosity real part of the permittivity predicted by the LLL and BG models was also seen to match well with that predicted by the Clausius-Mossotti (CM) relation and the additivity rule of ionic polarizability (ARIP) (Figure 1).

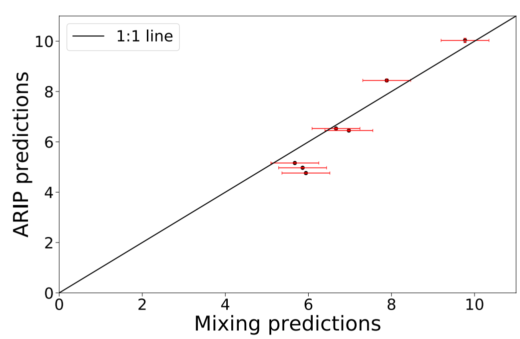

Figure 1: Comparison of LLL mixing predicted and CM/ARIP predicted zero-porosity real part of the permittivity for the seven samples measured in this study.

The ARIP theory states that the molecular polarizability of a substance can be calculated from adding the relative contributions of the individual ion polarizabilities making up that substance [7]. The CM and ARIP theories were previously shown to accurately predict the real part of the permittivity for numerous silicate minerals in [7]. Combined, the CM and ARIP theories allow the prediction of the zero-porosity real part of the permittivity for a specific mineral, based on its chemistry and unit cell dimensions. As asteroid regolith is a complicated mixture of many minerals, the linear correlation observed between a materials grain density and the real part of the permittivity is more useful than applying the CM and ARIP theories in inferring asteroid surface properties. We incorporated this relation into our previous asteroid radar model in [4], which was an extension of the empirical model introduced in [1] and [8]. To apply this asteroid radar model to a specific asteroid, the average grain density of the regolith material is required. As a first guess, this can be approximated by the grain density of an asteroid's likely meteorite analog.

Discussion: The asteroid radar model derived in the current study was applied to seven asteroids that either have been, or are currently targeted by robotic spacecraft missions: 101955 Bennu, 253 Mathilde, 433 Eros, 21 Lutetia, 25143 Itokawa, 4 Vesta, and 4179 Toutatis. The resulting porosity calculations from our model are compared with similar estimates derived from the earlier model (uncalibrated) of [1] and [8], and with bulk porosity estimations (representing the entire body) using values taken from the literature (Figure 2).

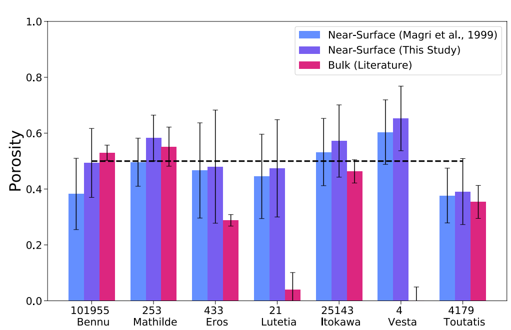

Figure 2: Asteroid surface porosities derived from radar data and bulk porosities from mass and volume estimates. The dashed line represents 50% porosity.

There is no statistically significant difference between the calculated porosity from the original model in [1] and [8] and the model presented in this work. This is not surprising, considering the original mixing model assumed in [1] and [8] was an empirical fit to a large dataset of permittivity measurements for a range of geologic samples. However, the model in [1] and [8] includes invalid assumptions about the material properties which are not considered in the error analysis, whereas our model is constrained by adhering to mixing theory that has been validated by our permittivity measurements. The mixing theory assumed in the asteroid radar model from [1] and [8] is based on the Lichtenecker mixing model, which was found to not match our experimental results well, and also assumes constant material permittivity and grain density, which in practice will vary for different asteroid surfaces. For 433 Eros, 21 Lutetia, and 4 Vesta, the asteroid radar models both predict significantly higher porosity in the near-surface when compared with the bulk porosity. This implies the presence of a porous regolith covering each body, which has been inferred from spacecraft observations. The application of our radar model is in agreement with experimentally verified mixing theory, and shows potential for use in determining if an asteroid surface is covered by regolith. An interesting result from Figure 2 is that for the seven asteroids considered, the near-surface porosities all generally fall around 50%, which is the average lunar regolith porosity within the first 30 cm of the lunar surface [9]. This agreement implies similar upper regolith properties among these asteroids and the Moon, which span different sized bodies and asteroid taxonomies. A preliminary conclusion from this is that regolith formation mechanisms on the Moon and asteroids are similar. The estimation of the material permittivity from radar data used in [1] and [8] that is used to derive a porosity is questionable, and may not be appropriate for asteroids with rough surfaces or significant metal content. Future efforts into determining material permittivity from radar data could produce more accurate asteroid regolith porosity estimates with the use of the mixing relations identified in the permittivity measurements from our study.

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