SURFACE MINERAL COMPOSITION MODELING OF 81 D-TYPE ASTEROIDS USING SHKURATOV RADIATIVE TRANSFER THEORY. G. M. Gartrelle[1], [1]University of North Dakota (gmgartr@gmail.com); P. S. Hardersen[2], [2]Trouvaille, LLC. (paul.hardersen@gmail.com); M. R. M. Izawa[3], [3]Institute for Planetary Materials, Okayama University (matthew.izawa@gmail.com); M. C. Nowinski[4], [4]The Boeing Company mcnowinski@gmail.com

Introduction: D-type asteroids are one of the most unique, complex, and compelling mysteries in the Solar System. Very little is known about their formation location, formation conditions, dynamic evolution, or surface mineral chemistry. These low albedo objects are extremely to detect and observe from Earth, and those which have been observed revealed no mineral absorption features to aid in constraining surface mineralogy.

Although no spacecraft has ever visited one and there are no confirmed samples of D-types in the terrestrial meteorite collection, there may be analogs found in interplanetary dust particles (IDP) [1]. D-types may or may not be related to comets [2, 3], outer planet satellites [4-6], Trans Neptunian Objects (TNO) [5, 7, 8], Kuiper Belt Objects (KBO) [9, 10], or the recently discovered interstellar visitor 1I/2017 U1, "Oumuamua" [11-13]. The presence of dark, spectrally red material in multiple classes of outer Solar System bodies implies the existence of a presently unknown cosmo-chemical connection between them.

This focus of this project was to determine if a plausible D-type surface mineralogy model could be constructed using radiative transfer theory. Shkuratov theory, an empirical method, calculates modeled surface reflectance from four inputs: an actual spectrum; the wavelength range; specified minerals and abundances; and refractive indices for the specified minerals [14]. This method has been used successfully over the years for multiple asteroids [15-19], including (10199) Chariklo a D-type Centaur [20].

Methodology:

A model using a combination of Interactive Data Language (IDL) and Python based code was developed based on a high-level specification written specifically for this project. A key assumption was the use of mineralogy of the ungrouped chondrites Tagish Lake (TLM), WIS 91600, and MET 00432 as the basis for surface chemistry due to established belief a D-type asteroid is the possible parent body of these meteorites [21-26]. Mineralogically well-constrained samples of TLM provided the base set of mineral inputs for the model [24, 27, 28]. These include magnesium-saponite, serpentine, siderite, calcite, magnetite, gypsum, dolomite, and several others. A group of spectral darkening, brightening, or reddening agents used in compositional modeling studies of featureless bodies such as tholin, enstatite, H_2O ice, CO_2 ice, iron powder, or metallic iron were included. Finally, common meteoritic minerals such as olivine and pyroxene complete the list.

Model testing, using varying mole fractions of olivine and TLM samples from Izawa et al, [27, 28] produced model spectra with excellent fits to the actual materials tested. Twenty-three D-type asteroid spectra covering the VNIR wavelength range (0.7-2.5 μm) were newly acquired from the NASA Infrared Telescope Facility (IRTF) using the SpeX instrument between 2016-2019. Another fifty-eight VNIR D-type spectra, also obtained using IRTF and SpeX, were provided though the literature [29-31]. Of the 81 D-types, 54 are Jupiter Trojans, with the balance distributed between Inner and Outer Belt, save for a single near-Earth asteroid and a single Centaur. The asteroid spectra were run through the Shkuratov model using a specified set of minerals and opaques to produce a model spectrum with a goodness of fit measurement and an uncertainty. Iterations were performed on each asteroid spectrum until the best fit model was found.

Results & Discussion:

Model Output. The general best-fit results from the subject D-types suggest a surface of abundant phyllosilicates and opaques coupled with low-iron (either $Fayalite_{10}$ or $Fayalite_{17}$) olivine (Table 1). Approximately half of the asteroids achieved best-fit model results with small amounts (<~3%) of water-ice. These results are generally consistent with prior discussion from the literature [20, 32, 33]. Two Outer Belt D-types with albedo >0.1 achieved best fit using ~1% enstatite in addition to the previously specified minerals, again consistent with previous work [34].

Statistical analysis of model results found a negative correlation between pyrrhotite abundance and semi-major axis (α) ($r(79) = -.337$, $P = <.01$) and a positive correlation between tholin abundance and (α) ($r(79) = .223$, $P = <.05$). This may account for spectral variations observed in the VNIR range for D-types based on Solar System location.

Model Performance. The model performance was generally good with best performance occurring at wavelengths <~2.0 μm. Root mean squared error (RMS) was calculated for each asteroid's best fit model and ranged from ± 0.0089 – 0.0839 with a mean RMS of ± 0.0357.

Areas of potential improvement to the model include, automation of the fitting process, expansion of the dataset to include the full complement of D-type spectra, additional minerals, more flexibility with grain size (fixed at 50 μm) as well as porosity, and most importantly, more refined refractive indices.

Table 1: Model abundance ranges for surface composition of 81 D-type asteroids. Note: Best fit models for individual asteroids contain either Fay_{10} (N=72) or Fay_{17} (N=9).

Mineral	Low	High	Mean	Std. Error (±)
Ol Fay_{10}	1.00%	12.00%	6.97%	0.03
OL Fay_{17}	3.00%	8.51%	5.90%	0.03
$Saponite_{mg}$	44.00%	56.95%	50.26%	0.02
Serpentine	0.00%	3.00%	1.07%	0.01
Magnetite	6.50%	12.55%	9.04%	0.01
Siderite	6.00%	13.10%	10.48%	0.01
Calcite	0.00%	10.93%	2.61%	0.03
Pyrrhotite	7.00%	24.53%	15.26%	0.03
Ice	0.00%	3.80%	0.71%	0.01
Dolomite	0.00%	3.27%	0.34%	0.01
Tholin	0.00%	12.45%	3.36%	0.03
Other	0.00%	2.23%	0.04%	0.00

Conclusions & Implications: The work conducted in this study determined the mineralogy of TLM is appropriate as a foundation for modeling the surface of D-type asteroids using VNIR asteroid spectra. That TLM samples represent a demonstrably close analog to D-type spectra has been observed and confirmed by multiple workers for close to two decades. The minerals used in the models for this work are representative of what would be found in the proposed formation location for these targets. While there are other mineralogic combinations which can approximate the observed spectra of the 81 targets, they would likely contain metallic iron, enstatite, or darkening agents in abundances that are unrealistic based on observed characteristics.

NASA's Lucy mission, scheduled for a 2021 launch, will be the first spacecraft to visit the Jupiter Trojans, including two D-types. The surface models in this work represent first approximations of D-type surface composition and will provide positive guidance to aid completion of the mission's science objectives.

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