APPLYING THE BUS-DEMEO ASTEROID TAXONOMY TO METEORITE SPECTRA. T. H. Burbine[1], S. M. Wallace[2], and M. D. Dyar[1]. [1]Department of Astronomy, Mount Holyoke College, 50 College Street, South Hadley, MA 01075, USA (tburbine@mtholyoke.edu), [2]Harvey Mudd College, 301 Platt Boulevard, Claremont, CA 91711, USA.

Introduction: Since the 1970s, asteroid reflectance spectra have been classified by a variety of systems using their visible and/or near-infrared spectra. The hope is that bodies with similar spectra have similar surface compositions.

The latest asteroid classification system is the Bus-DeMeo taxonomy [1], which classifies asteroid reflectance spectra from 0.45 to 2.45 µm (**Figure 1**). Very red-sloped objects are given the "w" notation after their classification. The goal of the Bus-DeMeo taxonomy is to better characterize the diversity of spectral properties of asteroids in both the visible and near-infrared.

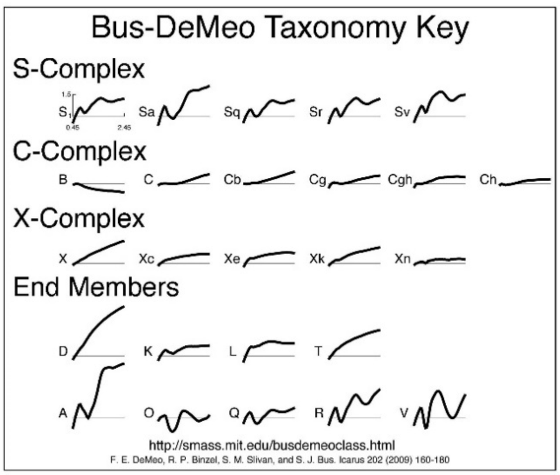

Figure 1. The Bus-DeMeo taxonomy. This figure is used with the permission of Francesca DeMeo.

Our group is investigating the application of more modern machine learning methods to classify asteroids. Our first step was to collect available asteroid and meteorite spectra and massage them all into the same format with carefully selected headers. A second step is to test the Bus-DeMeo classifier on a group of spectra for which it ought to excel: laboratory spectra of meteorites since almost all meteorites are believed to be fragments of asteroids. Subsequent steps involve using two common machine learning classification algorithms: logistic regression and K-nearest neighbor [2] and testing them on the meteorite spectra to compare their results. The second of these steps forms the basis for this abstract.

Background: An asteroid's taxonomic classification is often used to predict the mineralogy for an object. For example, S-complex and Q-type asteroids are often assumed to have ordinary chondrite mineralogies due to these bodies tending to have spectral properties arising from olivine and pyroxene. This assumption is partially justified by the returned sample from S-complex asteroid (25143) Itokawa having an LL chondritic mineralogy [3]. C-complex bodies are often expected to be related to carbonaceous chondrites due to their relatively flat spectral slopes and suppressed spectral features. A-type asteroids appear to be olivine-dominated due to their distinctive 1 µm features. V-type asteroids are presumed to have mineralogies similar to HEDs (howardites, eucrites, diogenites) due to their distinctive spectral features due to pyroxene.

To assess the robustness of the Bus-DeMeo taxonomy, this project uses reflectance spectra of meteorites gathered from the Keck/NASA RELAB (Reflectance Experiment Laboratory) database. To our knowledge, this is the largest available collection of meteorite spectra. These data allow us to pose several different questions. How well does the Bus-DeMeo taxonomy mineralogically classify reflectance spectra? Are there meteorite groups that do not classify "well" in the Bus-DeMeo taxonomy? What are the broader implications of these results for the applicability of the taxonomy?

Data: During the summer of 2018, we downloaded meteorite spectra from the RELAB database. These spectra included some unreleased data graciously made available to us by Ralph Milliken and Takahiro Hiroi. Wavelength coverage was ~0.3 to ~2.6 µm and were acquired using their near-ultraviolet, visible, and near-infrared bidirectional spectrometer. The measured phase angle was primarily 30°. Spectra included those of sieved material, bulk powders, irradiated samples, slabs, chips, and separated components.

Over 1,400 spectra from approximately 600 different meteorites were included in our subsequent analysis. Approximately 30% of the spectra were from ordinary chondrites, ~30% were from carbonaceous chondrites, and ~20% were from HEDs. The number of spectra from a particular meteorite group is a function of availability and scientific interest and does not, of course, reflect actual fall statistics.

Analysis: All spectra were classified using the Bus-DeMeo Taxonomy Classification program in batch mode, which was generously made available by Stephen Slivan to speed up the classification process. The program outputs one of three possibilities: 1) a classification; 2) a notice that further inspection is needed to differentiate between a number of classes; or 3) an indeterminate classification indicating that the spectrum could not be classified. Only 56% of the spectra could be uniquely classified by the automated scheme, 42% needed further inspection, and 2% were indeterminate. All spectra that needed further inspection were classified visually. Some were easy to differentiate (e.g., either D-type or A-type). Some were much more difficult (e.g., either Xk-type, Xc-type, Xe-type, C-type, Ch-type, or Xn-type) due to more subtle spectral differences that could not be easily differentiated by the computer program. All of the resulting classifications are displayed in **Table 1**.

Results and Discussion: Many results were readily apparent and expected. Almost all the spectra classified as V-types are from HEDs. Meteorite spectra classified as A-types and T-types are extremely rare. Spectra classified as S-complex and Q-type objects are primarily from ordinary chondrites.

The biggest surprise from this test was the large number of spectra that could not be classified without "human intervention." This result suggests that the existing Bus-DeMeo classifier might be ready for revision using a more modern discerning algorithm than what was used in the original system, which was based on principal component analysis and visual examination.

Spectra of a few meteorite groups do not classify "well" using the Bus-DeMeo taxonomy. For example, many of the brachinite spectra either classify as indeterminate or as needing visual examination to discriminate between different types of C-complex or X-complex spectra. Brachinites have distinctive olivine features but are not red-sloped in the visible and near-infrared. The Bus-DeMeo system is unable to "accurately" classify these "flat"-sloped olivine-dominated meteorites. Asteroids with olivine-dominated spectra tend to be much redder in slope than brachinites.

Table 1. Percentages of RELAB meteorite spectra classified as a particular Bus-DeMeo asteroid class.

Asteroid Class	%	Asteroid Class	%
A-type	<1	S-complex	18
C-complex	15	S-type	6
B-type	8	Sa-type	<1
C-type	5	Sq-type	6
Cb-type	<1	Sr-type	3
Cg-type	<1	Srw-type	<1
Cgh-type	1	Sv-type	1
Ch-type	<1	Svw-type	<1
D-type	3	Sw-type	1
Indeterminate	2	T-type	<1
K-type	12	V-type	16
L-type	5	Vw-type	1
O-type	<1	X-complex	12
Q-type	14	X-type	3
R-type	1	Xc-type	4
		Xe-type	<1
		Xk-type	4
		Xn-type	<1

In addition, all of the resulting asteroid classes contain a variety of different meteorite types. For example, only ~50% of the C-complex spectra are for carbonaceous chondrites. The other ~50% include the spectra of aubrites (because visual albedo is not used in the taxonomy), ordinary chondrites, and ureilites. This result is expected since there are numerous ways to produce meteoritic material with subdued spectral features. This result is consistent with the source body (2008 TC_3) of the polymict ureilite Almahata Sitta being classified as a C-complex body from its visible spectrum [4]. The D-types are another Bus-DeMeo class with a mix of meteoritic analogs. Approximately 60% of the meteorites with D-type spectra are carbonaceous chondrites (e.g., CM2, Tagish Lake). However, the other ~40% are primarily iron meteorites due to their red spectral slope.

Conclusions: This study shows the successes and limitations of the Bus-DeMeo taxonomy in mineralogically classifying reflectance spectra. It works effectively in classifying objects with distinctive absorption bands. However, the Bus-DeMeo classifier is challenged to differentiate objects with more subtle features. This suggests that development of a more modern taxonomy may be timely. We are working to develop a new classification system using both asteroid and meteorite spectra that may better encompass the diversity of mineralogies found in these bodies. An asteroid taxonomy using machine learning, where a computer program has the ability to automatically learn and improve from experience, has the advantage of being easily updated and conveniently (and universally) applied, avoiding the need for visual inspection of spectra. We expect such approaches to generate the next-generation of asteroid taxonomies.

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