Challenges in Physical Characterization of Dim Space Objects: What can we learn from NEOs

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ABSTRACT

Physical characterization of dim space objects in cis-lunar space can be a challenging task. Of particular interest to both natural and artificial space object behavior scientists are the properties beyond orbital parameters that can uniquely identify them. These properties include rotational state, size, shape, density and composition. A wide range of observational and non-observational factors affect our ability to characterize dim objects in cis-lunar space. For example, phase angle (angle between Sun-Target-Observer), temperature, rotational variations, temperature, and particle size (for natural dim objects). Over the last two decades, space object behavior scientists studying natural dim objects have attempted to quantify and correct for a majority of these factors to enhance our situational awareness. These efforts have been primarily focused on developing laboratory spectral calibrations in a space-like environment. Calibrations developed correcting spectral observations of natural dim objects could be applied to characterizing artificial objects, as the underlying physics is the same. The paper will summarize our current understanding of these observational and non-observational factors and present a case study showcasing the state of the art in characterization of natural dim objects.

1. INTRODUCTION

Impacts due to near-Earth objects (~90% NEAs and ~10% comets) are one of the natural hazards that can cause the extinction of the human race, but one that can potentially be mitigated if the threat is detected with sufficient lead-time. While the probability of such an event is low, the outcome is so catastrophic that we are well justified in investing a modest effort to minimize this threat. Historically, asteroid impacts have altered the course of evolution on the Earth. The most recent significant event took place 65 million years ago when a 10-km object impacted off the Yucatan Peninsula coast, Mexico, leading to the extinction of dinosaurs and ~75% of all species (e.g., Alvarez et al., 1980). This probably provided mammals (including our ancestors) an opportunity to thrive.

Within our lifetime, the collision of Comet Shoemaker-Levy 9 (SL-9) with Jupiter served as reminder to us that asteroid impacts could be a real threat to life on Earth. The probability of such impacts appears to be significantly higher than initial estimates with the recent discovery of at least three asteroid/comets impacts on Jupiter. More recently, the Chelyabinsk meteor over Russia, which injured hundreds of people and damaged thousands of buildings, only reinforced the importance of detecting and characterizing small NEAs that pose a greater threat than most large NEAs discovered so far. Following the SL-9 impact, the U.S. Congress-mandated NEO searches have been very successful with over 14,800 NEOs discovered as of September 2016 (IAU Minor Planet Center Page).

While the discovery of large NEOs has been largely successful, physical characterization efforts have lagged behind with only a fraction of the NEO population having accurate rotation periods and compositional information. For most NEAs, sizes are not actually measured but have been estimated based on the absolute magnitude *(H)* and assumed albedos of 5% and 25%. This provides a gross estimate of size. However, the associated uncertainty in volume (and hence mass and potential impact energy) is more than a factor of ten, even ignoring the uncertainties in densities. Actual albedo and size determinations using either thermal infrared radiometry or the near-IR reflectance curve method have been made for ~15% of NEO population. Taxonomic classifications, including ambiguous types, are available for ~15% of the known NEA population (Binzel, personal communication). Actual compositional determinations and/or established meteorite affinities are available for ~2% of the known NEA population.

The Planetary Defense Coordination Office (PDCO) has developed a characterization flow chart (Fig. 1) to streamline the process of acquiring the most relevant pieces of information in case of an impending NEO impact. This decision make chart could be used as a template for characterizing RSOs in Earth orbit.

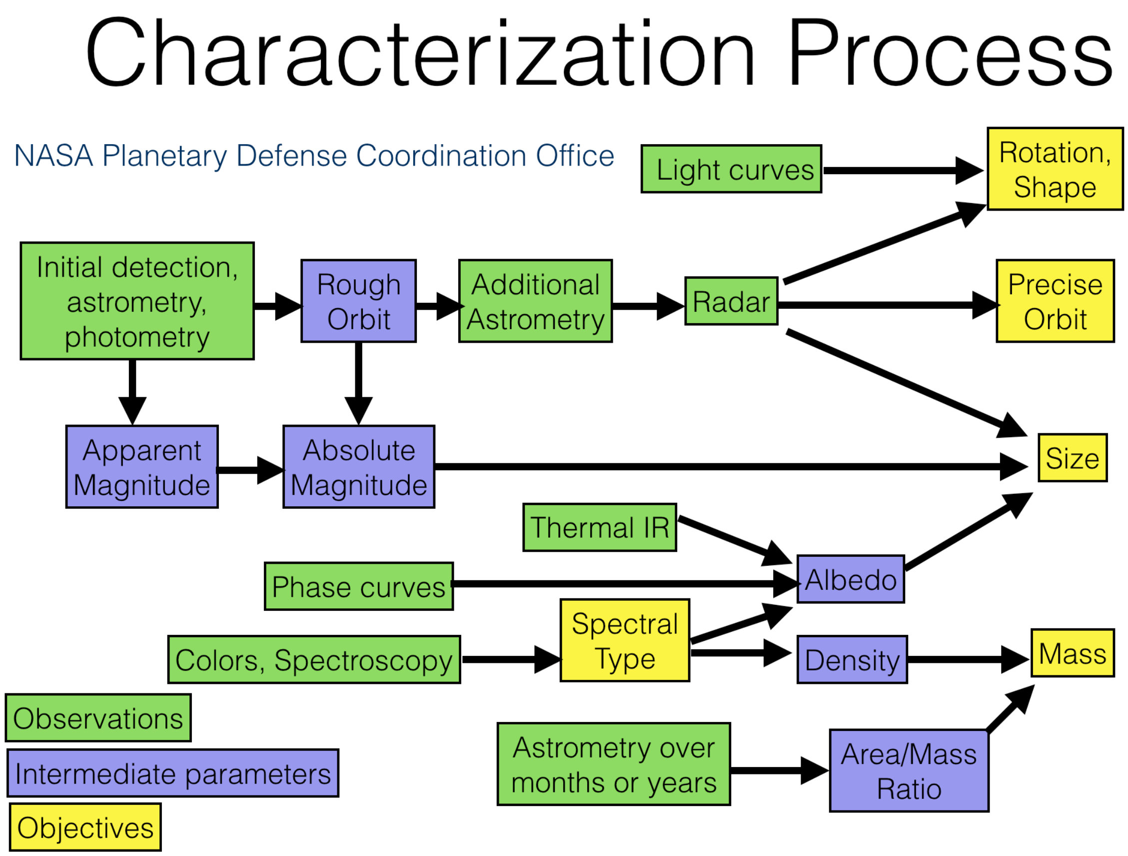

Figure 1. Near-Earth Object characterization process where pathways to achieve specific objectives are met by a set of observations with EO and radar sensors. Some objectives can be achieved by more than one type of observation.

Visible/near-infrared (VIS/NIR) spectra (0.3-2.5µm) have been widely used to determine mineral abundances and compositions of asteroids and remote space objects (RSOs) in Earth orbit. Prior to mineralogical interpretation, spectral band parameters must be corrected for non-compositional effects, such as temperature, phase angle, and grain size. Phase angle is defined as the Sun-Target-Observer angle and is typically less than 25° for main belt asteroids but can be much higher and changes rapidly for near-Earth asteroids and RSOs. With increasing or decreasing phase angle, the slope of a reflectance spectrum generally becomes redder or bluer respectively, an effect known as phase reddening. Temperature differences between space environment and laboratory room temperature measurements produce changes in absorption band centers, band depths, band widths, and band area ratios. Of these factors, temperature corrections of band centers have a large impact on mineralogical characterization, whereas phase angle corrections are important for constraining space weathering, as they affect spectral slope, albedo, and band depth. Here we present a summary of our current state of the knowledge in constraining these observational effects and the importance of correcting them prior to interpretation of RSO spectral data.

2. EFFECT OF TEMPERATURE VARIATIONS ON SPECTRA

Temperature variations are known to produce changes on the NIR spectra of minerals and compounds. These changes are seen as a broadening (or narrowing) of the absorption bands and as a shift in the band centers (Singer and Roush, 1985; Schade and Wäsch, 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002). The width of an absorption band is related to the amplitude of the thermally induced vibrations of the cation about the center of the site. Thus, an increase in temperature will lead to an increase in the amplitude of the thermal vibrations of the cation, resulting in a broadening of the absorption band. This will also produce an expansion of the site, leading to an increase in the cation-oxygen interatomic distance. As a result, the crystal field splitting energy will decrease, shifting the absorption bands to longer wavelengths (Burns 1993). Figure 2 shows the NIR spectra of the H5 ordinary chondrite meteorite Allegan obtained at two different temperatures by Hinrichs and Lucey (2002). The broadening of the absorption bands is evident when the temperature is increased from 100 K (top) to 400 K (bottom).

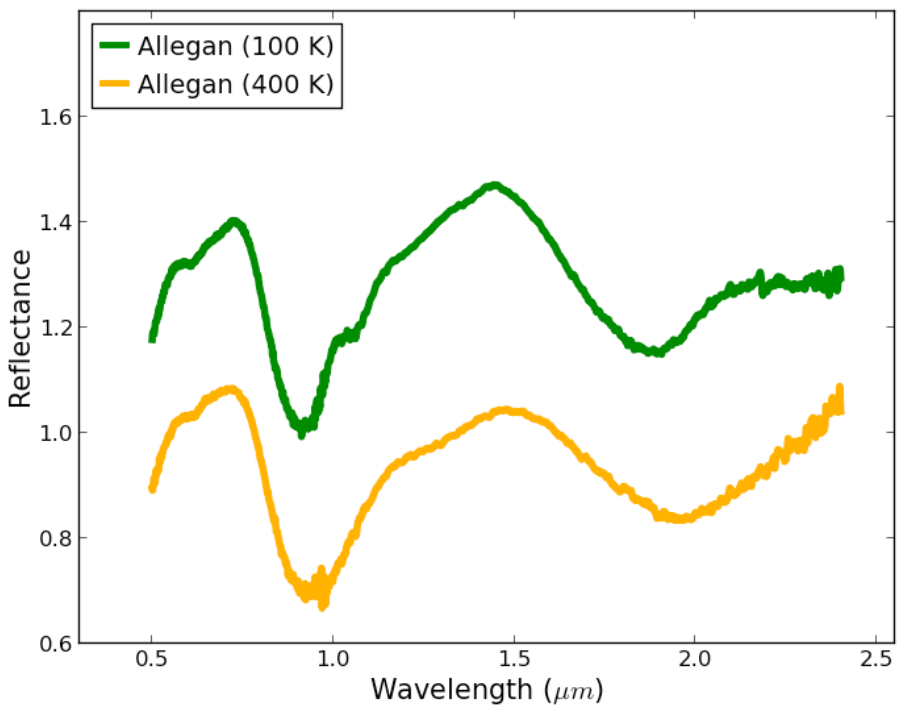

Figure 2. NIR spectra of the H5 ordinary chondrite Allegan obtained at two different temperatures. Spectra have been offset for clarity. The spectrum at the top was collected with the sample at 100 K, while the spectrum at the bottom was obtained with the sample at 400 K. Data from Hinrichs and Lucey (2002).

Band parameters like Band centers are used along with laboratory spectral calibrations to determine the composition of both natural and artificial moving objects (e.g., Dunn et al. 2010, Burbine et al. 2007, Reddy et al. 2011). However, these spectral calibrations are derived from spectra of meteorites, and mineral and space material samples obtained at room temperature (300 K), while the average surface temperature for NEAs/RSOs can range from ~ 130 to 440 K (e.g., Hinrichs et al. 1999; Moroz et al. 2000, Sanchez et al. 2012). Therefore, prior to the compositional analysis, temperature corrections to the band parameters must be applied. For this purpose, temperature corrections for different types of minerals and meteorites have been developed (e.g, Burbine et al. 2009; Reddy et al. 2012; Sanchez et al. 2012, 2014). Similar protocols need to be developed for artificial material in the laboratory to enable spectral characterization of RSOs.

3. EFFECT OF PHASE ANGLE VARIATIONS ON SPECTRA

The phase angle is defined as the angular separation between the Sun and the observer as seen from the target. An increase in phase angle produces an effect known as phase reddening, which is characterized by increasing the spectral slope and producing variations in the intensity of the absorption bands of visible and NIR spectra (e.g., Gradie et al. 1980; Luu and Jewitt 1990; Reddy et al. 2012; Sanchez et al. 2012). This effect is explained as the result of the wavelength dependence of the single-scattering albedo (Gradie et al. 1980, Gradie and Veverka 1986, Clark et al. 2002). Figure 3 shows the NIR spectra of the LL6 chondrite meteorite Dhurmsala obtained at three different phase angles by Sanchez et al. (2012). An increase in spectral slope and variations in the band depths can be seen as the phase angle increases from 13° to 90°.

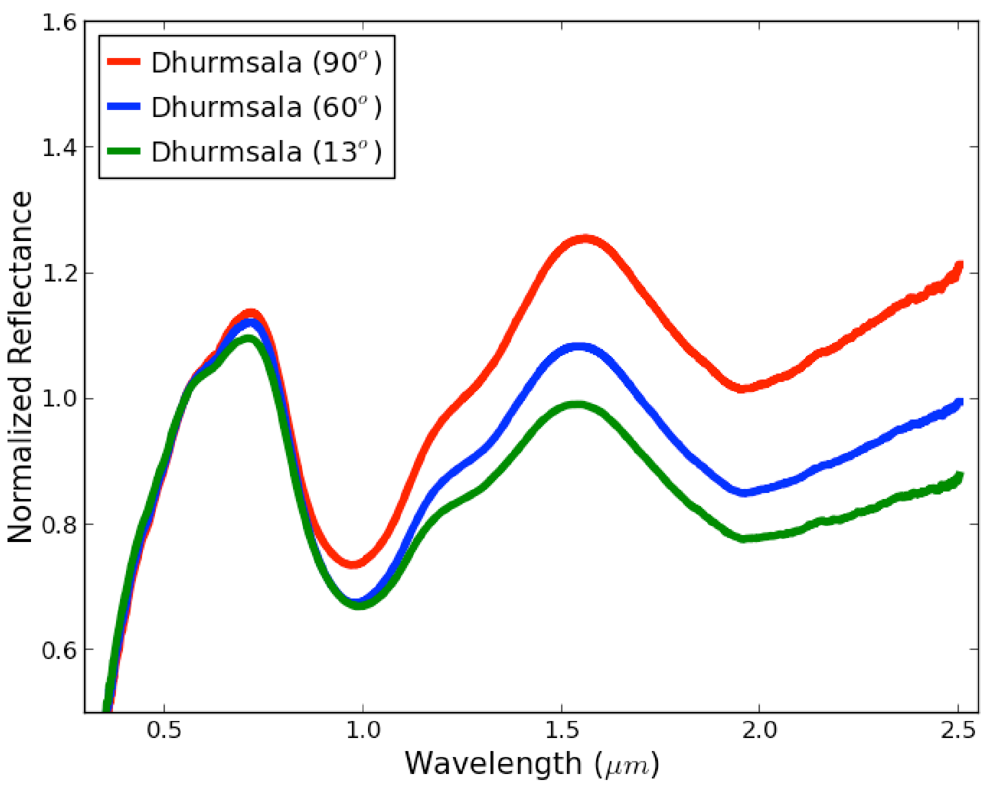

Figure 3. NIR spectra of the LL6 chondrite Dhurmsala obtained at three different phase angles. From the bottom to the top: 13° (green), 60° (blue), and 90° (red). All the spectra are normalized to unity at 0.55 μm. Figure adapted from Sanchez et al. (2012).

NEAs and RSOs are prone to exhibit phase reddening because they are typically observed at rapidly changing phase angles. Sanchez et al. (2012) found that phase reddening could lead to an ambiguous taxonomic classification when the same asteroid is observed at different phase angles. This is equally applicable to RSOs in all orbits as the phase angle changes rapidly as the object rises, reaches the opposition point, and sets. From their study they derived empirical equations that can be used to correct the effect of phase reddening in the band depths. Sanchez et al. (2012) also demonstrated that phase reddening can mimic space weathering, since both effects are manifested in a similar way. They concluded that phase reddening should be considered when studying space weathering effects on spectral data.

4. EFFECT OF GRAIN SIZE VARIATIONS ON SPECTRA

NIR spectra can be also influenced by the grain size on natural moving object. The amount of light scattered and absorbed by a grain is proportional to the optical pathlength, therefore an increase in grain size will produce an overall decrease in reflectance (e.g., Clark 1999). This can be seen in Figure 4, where we plot the spectra of the LL4 ordinary chondrite Soko-Banja for samples with two different grain sizes. The spectrum corresponding to a grain size of 90-180 μm has a much lower reflectance than that corresponding to a grain size of < 90 μm. A change in the intensity of the absorption bands and spectral slope is also evident. Differences in grain size are likely the responsible for the discrepancies seen between NIR spectra of small NEAs (< 10 m in diameter) and meteorite analogues, as recently demonstrated by Reddy et al. (2016). The weak gravity field of small NEAs makes it difficult for these objects to retain a regolith layer, resulting in a surface more similar to bare rock. Due to this difference in grain size, the spectra of these objects tend to have negative slopes compared to the spectra of meteorite samples, which are normally crushed and sieved to a specific grain size. For this reason, knowledge of the sample grain size is required if radiative transfer models (e.g., Hapke, 1981, 1984, 1993; Shkuratov et al. 1999) are employed to model asteroid reflectance spectra.

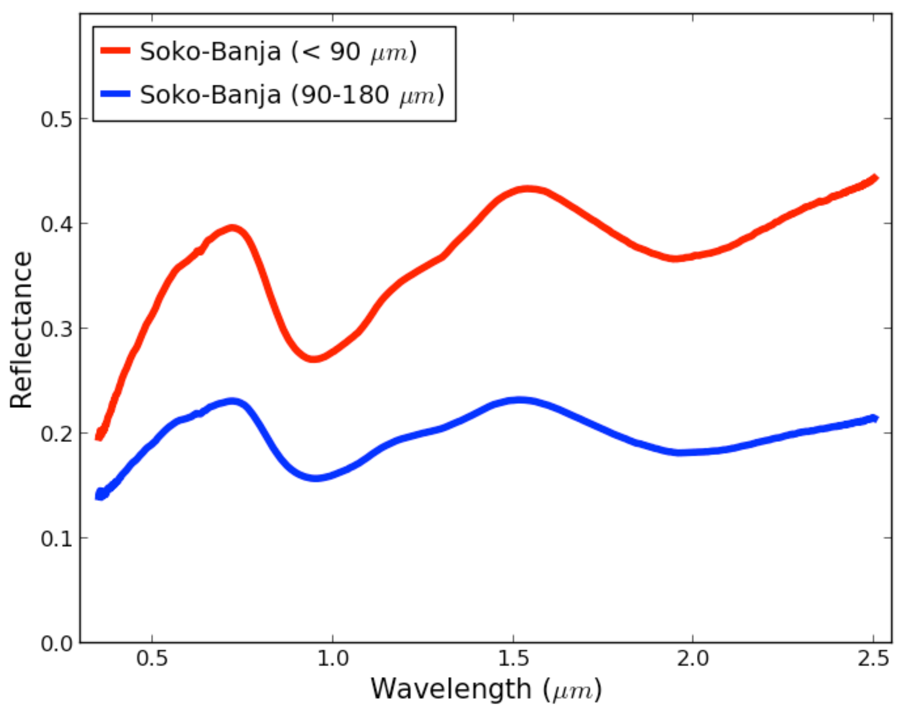

Figure 4. NIR spectra of the LL4 ordinary chondrite Soko-Banja for two different grain sizes, < 90 μm (top) and 90-180 μm (bottom). Data obtained from the University of Winnipeg HOSERLab.

5. EFFECT OF SPACE WEATHERING ON SPECTRA

Space weathering is process by which the surface optical properties are modified when exposed to space environment in the absence of an atmosphere. On the moon, the primary effect of space weathering is a decrease in optical albedo, increase in spectral slope (reddening), and a decrease in absorption band depth (Pieters et al. 2000; Taylor et al. 2001). Space weathering trends observed by spacecraft on asteroids (Vesta, Itokawa, Ida and Eros) suggest unique styles of space weathering operating on each of these objects (Gaffey, 2010). These unique styles of space weathering could be related not only to their heliocentric distance but also their surface composition. Similarly, surface albedo and spectral properties of RSOs would be modified in the near-Earth environment making it challenging to uniquely identify their composition.

6. EFFECT OF VACUUM ON SPECTRA

The effects of high vacuum on minerals and their NIR spectra have not been investigated in detail, since most laboratory measurements are obtained under terrestrial conditions at 1 atm, i.e., approximately the air pressure at Earth mean sea level (equivalent to 760 torr). At the ultra high vacuum of the space (10^{-6} to 10^{-9} torr), however, outgassing, which is the release of volatiles from minerals (or materials in general), occurs. Thus, the effect of vacuum on hydrated minerals will be of particular importance. Hibbitts et al. (2012) investigated the effects of vacuum desiccation on the NIR (1.7-5.5 μm) spectra of clays. Their measurements were obtained under ambient conditions and high vacuum (10^{-7} torr). They found that the water band at 1.9 μm shrinks under high vacuum after desiccation, while the 3 μm band narrows and shifts to longer wavelengths. The narrowing of the 3 μm band will also result in an overall increase in brightness in the 3.5-5 μm region after desiccation. These effects must be taken into account when investigating the presence of hydrated minerals on primitive asteroids like C-types. Hence, studying minerals and materials commonly associated with artificial moving objects under similar environmental conditions, can help in the analysis and interpretation of the data.

7. CASE STUDY: CHARACTERIZING SMALLEST NEO

Physical characterization of natural objects such as NEOs using ground-based telescopes is the only way to meet several objectives for impact hazard assessment and mitigation as outlined in Fig. 1. Combining multi-wavelength observations can yield complimentary information that can be used to confirm or reject a hypothesis. Correcting for observational effects is vital for a robust physical characterization as demonstrated in previous sections of this paper. On October 12, 2015, a 2-meter diameter near-Earth asteroid 2015 TC_{25} made a close flyby of the Earth at a distance of 69,000 miles. We physically characterized this NEA using ground-based optical, near-infrared and radar assets to constrain its rotation state, surface composition, meteorite analogs, and source region in the main asteroid belt. For the rotational study we used data from the 4.3-m Lowell Discovery Channel Telescope (DCT), the 3-m NASA Infrared Telescope Facility (IRTF), and the 2.4-m Magdalena Ridge Observatory (MRO) telescope. Using this lightcurve, we determined that 2015 TC_{25} is a fast rotator with a rotational period of about 2.23 min (133.8 seconds). Using the lightcurve amplitude of 0.40 mag and asymmetric peaks of approximately 0.08 mag, we suggest that the object has an irregular shape.

We also observed the NEA with Arecibo Observatory S-band (2380 MHz, 12.6 cm) radar. This consisted of transmitting a circularly polarized, monochromatic tone for approximately the time taken for light to reach the asteroid, reflect, and return to the 305-m antenna followed by reception of the echo in both the same-circular (SC) and opposite-circular (OC) polarizations for a similar amount of time. The polarization ratio SC/OC was 1.10 ± 0.23 and 0.77 ± 0.15 (one-sigma) on October 17 and 18, respectively. Combining the observations from two nights suggests a polarization ratio of ~ 0.9 with a possible range of 0.62 – 1.33. These values are significantly elevated compared to S- and C-complex asteroids (Benner et al. 2008) with mean polarization ratios of 0.27 and 0.29, respectively, but are consistent with the range of polarization ratios measured for known E-type asteroids of 0.74 – 0.97.

Near-infrared spectroscopic observations of 2015 TC_{25} were obtained remotely using the SpeX instrument in prism mode on NASA IRTF (Rayner et al. 2003) on 12 October 2015 between 8:22-9:35 UTC when the asteroid had a V magnitude of 17.5 and a phase angle of 32°.The spectrum of 2015 TC_{25} had a weak absorption band at 0.9 μm and a negative spectral slope (decreasing reflectance with increasing wavelength) beyond 1.1 μm. We found that 2015 TC_{25} has a Band I center of 0.905 ± 0.003 μm, and a Band

I depth of 5.4±0.2%. Due to their relatively small heliocentric distance, low albedo NEAs show a distinct upturn in reflectance (shorter wavelength end of the Planck curve) in near-IR wavelengths beyond 2.0-μm. 2015 TC_{25} does not show any evidence of such an upturn suggesting a moderate-high surface albedo consistent with E-type asteroids. E-type asteroids in the main belt are mainly concentrated in the Hungaria region at ~1.9 AU, although some of them have been also found dispersed throughout the inner part of the main belt from ~2.1 to 2.7 AU. These objects have been traditionally linked to the enstatite achondrite meteorites (aubrites) based on their high albedos and spectral shape. The overall shape of the spectrum and band parameters of 2015 TC_{25} are consistent with E-type asteroids such as (44) Nysa.

8. SUMMARY

Observational effects on spectra of moving objects hinder our ability to robustly characterize them. Understanding these effects and developing calibrations to mitigate them is vital for better understanding of their surface properties. We have presented a summary of the work that has been carried out over the last few decades for natural moving objects. These efforts have led to our ability to accurately characterize a fraction of NEOs making close flybys of the Earth each month. Our case study presented here shows that using multi-wavelength observations, objects as small as two-meters can be characterized even when they are at a distance of 66,000 miles from the Earth (significantly further than most RSOs). We are currently in the process of setting up a state of the art laboratory spectral facility at the University of Arizona that would enable us to understand these spectral effects under space-like conditions.

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