

COMPOSITIONAL AND PHYSICAL CHARACTERIZATIONS OF NEOs FROM VNIR SPECTROSCOPY

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Abstract

The masses and physical strengths of Near Earth Objects (NEOs) are needed to accurately assess their hazard potential and to explore possible mitigation strategies in detail. Obtaining sophisticated mineralogical characterizations of individual NEOs are critical to establishing their physical nature (compositions, intrinsic densities and strengths) and their properties (size and albedo, internal structure, gross strength). Near-infrared (NIR ~0.75-2.5 μm) and visible & near-infrared (VNIR ~0.4-2.5 μm) spectra of NEOs provide a means of sophisticated compositional determinations and in many cases determinations of - or strong constraints on - NEO albedos and sizes. For the binary NEOs - which constitute approximately a sixth of the NEO population - mass and bulk density determinations can be combined with intrinsic density determined from composition to yield constraints on internal structure and overall strength (i.e., strong solid rock versus strengthless rubble pile).

What Information Must NEO Characterizations Provide?

Several specific types of information are required in order to assess the hazard potential of NEOs - and of the various NEO subpopulations - and to evaluate possible mitigation strategies. First and foremost is

detection and orbit determination. This information is provided by search programs and follow-up observations. Once an object is identified as a potentially hazardous object / asteroid (PHO/PHA), several other critical pieces of information are needed to estimate its hazard potential and to evaluate possible mitigation strategies.

Mass and physical strength are the two most critical parameters. Mass along with impact velocity derived from the orbital parameters determines the kinetic energy of the NEO. Kinetic energy in turn provides an estimate of the gross destructive potential of the body should it collide with the Earth. Physical strength is a critical factor since it will determine where the kinetic energy is deposited for a significant range of impactor sizes. A physical strong body (e.g., an essentially intact solid body) is more likely to penetrate the atmosphere and to directly impact the surface generating a crater, ejecta, and a seismic and/or tsunami event. A physically weak body (e.g., an essentially strengthless rubble pile) is more likely to disaggregate during atmospheric entry depositing its energy as an airburst (by analogy to nuclear explosions) which - if the body is sufficiently large - can produce death and destruction over a large region from the shockwave and flash heating.

There are several approaches to determining the mass and strength of an NEO. For an object on a collision course, the final determination of these parameters would almost certainly be done from a rendezvous spacecraft in order to optimize the mitigation effort. However, long before such an *in situ* characterization, there are a variety of techniques that could provide very important constraints on these properties. Such

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constraints would govern the nature of the rendezvous mission and early mitigation planning. And in the more general case, the determination of these parameters for the NEO subpopulations would allow a much better definition of criteria for establishing hazard thresholds and for defining broad mitigation strategies.

In the ideal case well-instrumented spacecraft would be sent to a representative sample of NEOs and PHAs to collect the relevant information from orbit or *in situ*. And in the case of a dangerous object on an impact trajectory, spacecraft characterization would be virtually mandatory. However, such a spacecraft fleet – investigating several score NEO targets - is not plausible in the present budgetary climate – nor would it be the most efficient use of resources at the present stage of our knowledge. Absent a flurry of NEO spacecraft missions, one of the most powerful techniques for determining the requisite NEO properties is ground-based NIR and/or VNIR spectroscopy. Combined with the results of broad band visual photometry, adaptive optics imaging and/or radar observations, VNIR spectroscopy provides a very powerful but relatively inexpensive and immediately implementable means of determining - or strongly constraining - NEO sizes and strengths.

Mineralogical Characterizations of NEOs

Sophisticated mineral characterizations are critical to establishing the physical nature of individual Near Earth Objects (NEOs) and of important NEO subpopulations such as the potentially hazardous asteroids (PHAs). Properly obtained, reduced and analyzed VNIR spectra can provide detailed mineralogical characterizations of many types of NEOs. Detailed mineralogy allows the identification of the most relevant physical analogues (e.g., closest meteorite type, etc.) constraining the intrinsic density and strength of the material comprising the individual

NEO. As discussed below, when such information is combined with size and mass determinations, bulk densities can be calculated and overall physical strength can be estimated.

It is very important to distinguish between the taxonomic classification of an NEO and the mineralogical characterization of an NEO. Although taxonomic classification derived from broadband colors or visible CCD spectra (e.g., 0.4-1.0 μm) can provide some useful broad constraints on the compositions of NEOs, the utility of such taxonomies are severely limited in the present context because they often lump very diverse materials together.

Classifying an NEO into one of the asteroid taxonomic groups (e.g., S-, C-, V-, M-, X-, etc.) is a useful first step. However, it falls far short of providing the requisite information needed to assess the hazard potential of that body or to evaluate potential mitigation strategies. For such purposes, taxonomic classification suffers from two critical shortcomings: (a) lack of compositional specificity, and (b) sensitivity to the space weathering processes operating on asteroid surfaces.

The limits of the compositional information provided by the various asteroid taxonomies are generally understood by experienced asteroid scientists, although these limits are too often ignored or glossed over in practice. It is accurate to state that:

With a few exceptions, determining the taxonomic class of an asteroid provides virtually no specific information on the composition or physical properties of that asteroid!

For example, classifying an asteroid as a C-type or an S-type is somewhat akin to the children's guessing game of "animal, vegetable, or mineral". Even after you've established that the unknown is an animal, you're left with a set of organisms ranging

from butterflies to Bengal tigers, and far beyond. (*You do not have enough information to decide whether to grab a butterfly net or run like hell!*) To further muddy the issue, the several different asteroid taxonomic classification systems are not equally robust.

In order to make this critical point clear, consider the range of compositional analogs that would be included in several of the major taxonomic types. Figure 1 shows ten diverse assemblages which would all be classified as S-type objects (or subtypes of the S-type,

Figure 1 - Ten different meteoritic or meteorite-type assemblages that would be classified in the general S-type taxonomic group. Thermal history is color coded (black = only sub-melting temperatures; pink - red = partial to complete melting and differentiation. The S(I) to S(VII) range among differentiated objects is indicated in blue. And the undifferentiated or partially differentiated S(IV) types are also indicated in blue.

KEY: OC = ordinary chondrites

CV3/CO3 = Type 3 Vigarano and Ormans-type carbonaceous chondrites.

CB/CH = metal-rich Bencubbenite chondrites.

Prim. Achon. = Primitive achondrites.

Diff. = differentiated.

OI = olivine.

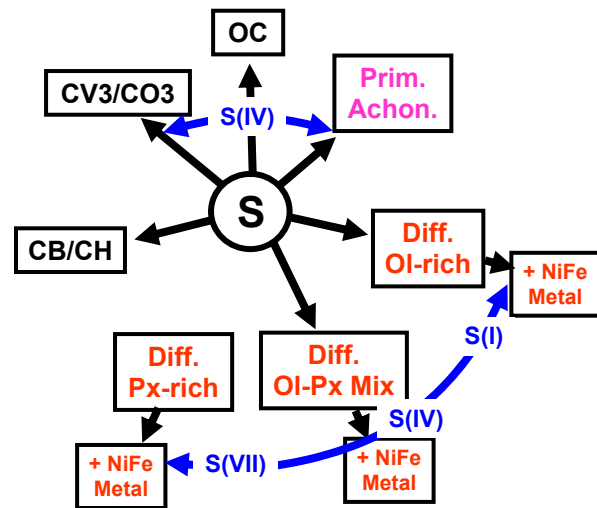
Px = pyroxene.

By contrast, the use of diagnostic spectral parameters (e.g., absorption band centers, relative band areas, etc.) to determine NEO mineralogy strongly constrains the origin and geologic history of that body. [Note: Although the prefix “geo” refers specifically to the Earth, by common consent the term “geology” has been adopted to refer to such processes on and within all solid solar system bodies.] The geologic history in turn strongly constrains the physical nature of the material making up the NEO and allows the best available physical analog (e.g., meteorite type, etc.) to be identified.

Albedo and Size Determinations from NIR Spectra

The determination of albedos – and hence sizes - is critical to any NEO hazard

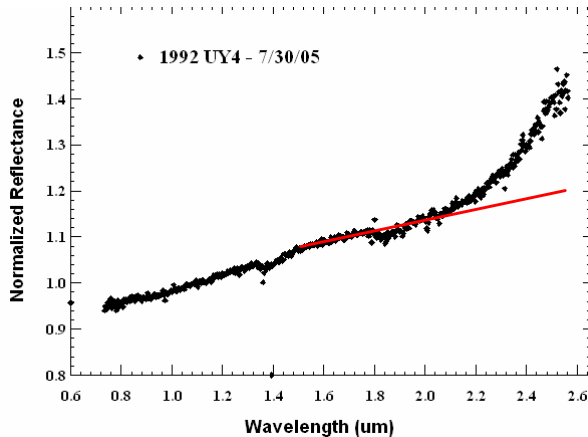
such as “L”). These ten represent a very wide range of thermal histories, parent body compositions and physical properties. **Intrinsic (zero porosity) densities of these assemblages range from ~3 to ~7 gm/cm³, and the physical (tensile) strength of intact bodies varies by many orders of magnitude.** The thermal history of these different types of materials – which strongly effects their physical properties - is indicated by the color coding.



assessment and mitigation program. The absence of direct albedo determinations for most NEOs means that their sizes are estimated assuming either a typical relatively high albedo (25%) or a typical relatively low albedo (5%). This produces a range of ~2.2 in estimated diameters and of ~11 in estimated masses, uncertainties which represent an order of magnitude uncertainty in the energy of a potential impactor. And considering the fact that the actual measured range of asteroid albedos is from <3% to >60%, and that NEO densities vary by at least a factor of five, the actual uncertainty in the kinetic energy of the potential impactor approaches two orders of magnitude!

For low albedo NEOs at heliocentric distances near 1 AU, thermal emission is observable in the long wavelength portion of

the 0.7-2.5 μm spectral interval (Figure 2). This flux excess can be used to determine the albedo of an NEO and (combined with a visual magnitude) its size. Abell (2003) and Abell *et al.* (2002) used the upturn beyond $\sim 2.1 \mu\text{m}$ in the reflectance spectrum of NEO 1998 ST₂₇ to derive an albedo ($5\% \pm 1\%$) for that object. For the specific heliocentric distance and phase angle of the NEO



observation, a Standard Thermal Model (STM) computer code (THERMFLX) was used to compute the albedo from the flux excess. The albedo was subsequently confirmed by an identical value calculated from the radar-derived diameter. Rivkin *et al.* (2005) later rederived this technique with slight modifications using data from Abell (2003).

Figure 2 - The unedited spectrum of PHA 1992 UY4 observed on July 30, 2005 with the SpeX instrument at the IRTF. The NEO was at a heliocentric distance of 1.075 AU. The weak features near 1.4 and 1.8-1.9 μm are incompletely corrected atmospheric absorptions. A linear continuum has been drawn through the linear portion of the spectrum between ~ 1.5 and $2.1 \mu\text{m}$. The sharp upturn longward of $\sim 2.1 \mu\text{m}$ is due to thermal emission. Initial analysis indicates an albedo of $\sim 5\%$.

For NEOs observed at small heliocentric distances ($< \sim 1.3$ AU depending on the albedo and phase angle), similar upturns in the spectrum can be used to directly determine their albedos or to establish the lower limit on their albedos. This spectral behavior readily identifies low albedo types and also discriminates the low albedo P-types from the spectrally similar but higher albedo M- and E-types. (In the absence of albedo information, E-, M-, and P-type objects are commonly lumped into the X-type.) Albedo determinations combined with observed visual magnitudes allow the direct calculation of NEO sizes. For higher albedo NEOs, this technique can establish a lower limit on the NEO albedo and an upper limit on the NEO size. Mineralogical characterizations – and the identification of plausible meteoritic analogs - can also constrain the albedo of an NEO to a much smaller range than that used presently and correspondingly reduce the uncertainty in body size.

Constraints on NEO Densities and Physical Strengths

Approximately the $1/6^{\text{th}}$ of the NEO population are binary objects (Margot *et al.* 2002). Accurate masses can be determined for such systems from the orbital periods and distances derived from radar, adaptive optics and lightcurve observations. Compositions derived from VNIR spectroscopy provide the intrinsic density of the constituent material. Sizes determined from VNIR-derived (or other) albedos and/or from radar data allow bulk densities to be computed from the mass and volume. The internal structure and physical strength of the NEO can be inferred from the comparison of the bulk and intrinsic densities. For example, an NEO with a bulk density significantly less than the intrinsic density must contain extensive pore volume and is highly likely to be a strengthless rubble pile. Conversely, if the bulk and intrinsic densities were similar, it would be a strong indication of solid body with little or no fracturing and hence a high physical strength.

For small (~100 – 250 m) NEOs, compositional determinations could refine the hazard assessment of the strong fast rotating monoliths (Whiteley *et al.* 2002). These bodies are rotating too fast to be held together by their own gravity and therefore must have significant tensile strength. They must be either essentially fracture-free stony bodies or metallic/metal-rich bodies. The difference would correspond to approximately a factor of two in mass and several orders of magnitude in physical strength. The metallic bodies would have approximately twice the kinetic energy and a significantly greater chance of penetrating intact to the surface than the stony bodies. This would effect the assessment of their hazard potential.

Space Weathering and NEO Compositional Characterizations

Spectral studies of asteroids from groundbased telescopes are likely remain our primary or sole means of characterizing the diversity of the NEO population for the immediate future. Although properly equipped asteroid spacecraft missions would obviously be preferable, in the present budgetary climate the number and timing of asteroid missions are highly uncertain for the foreseeable future. And a limited number of missions would only sample a fraction of the diversity in the asteroid population. Moreover, spacecraft missions are no panacea. Operational difficulties and instrumental limitations have limited – to a greater or lesser degree – the scientific return from all four spacecraft that have encountered asteroids to date (Galileo, NEAR, Deep Space I, Hayabusa). And in virtually all cases, groundbased characterizations were a critical input to obtaining the maximum scientific return from those encounters.

NEO spectral data can be analyzed by several general techniques:

i) Spectra or color data can be sorted into different taxonomic groups using a variety of

techniques. The taxonomic classes group together objects based on similar data parameters. The asteroid taxonomic types are derived by this method.

ii) Spectra can be analyzed by comparison to a set of reference spectra by the process of curve matching. This can be by visually matching spectra or by digitally searching for the match with the smallest net differences. Because of the limited comparison set and because of the effects of space weathering (see below), this approach has generally been of dubious value except for certain special cases.

iii) Spectra can be analyzed by the identification of spectral features (most commonly absorption bands) for specific minerals and the extraction of their diagnostic parameters such as band centers and relative band areas. These parameters are then interpreted using calibrations derived from laboratory studies and based in crystal field theory (e.g., Gaffey *et al.* 1993a,b; 2002)

Spectral slope and band intensity are critical parameters in virtually all of the asteroid taxonomic classifications. Similarly, spectral slope and band intensity are major factors in the curve matching approach. Unfortunately, these properties are known to be affected by processes operating in the space environment and grouped collectively as “space weathering”. The best understood example is the Lunar-style space weathering process which modifies the spectral slope, band intensities and albedo of the soils on the lunar surface (e.g., Pieters *et al.* 2000; Noble *et al.* 2001; Taylor *et al.* 2001; Hapke 2001).

Although a lunar style space weathering process has also been invoked for asteroid surfaces, it is evident that the asteroid situation is more complex. Figure 3 compares the apparent space weathering trends on asteroids 243 Ida (a Galileo flyby target) and 433 Eros (the NEAR orbiter target) to that seen on the moon. It is evident that different processes are operating on each of these three bodies. Data

from the Hayabusa mission to 25143 Itokawa are not yet fully calibrated, but initial

examination of that data suggests that Itokawa does not follow the lunar pattern either.

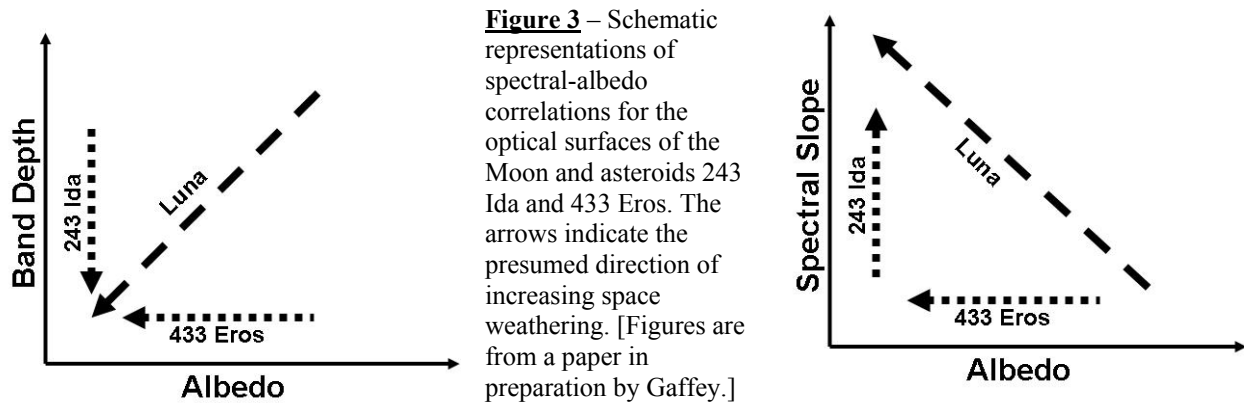


Figure 3 – Schematic representations of spectral-albedo correlations for the optical surfaces of the Moon and asteroids 243 Ida and 433 Eros. The arrows indicate the presumed direction of increasing space weathering. [Figures are from a paper in preparation by Gaffey.]

Since the asteroid taxonomic classifications and the curve matching techniques are both sensitive to spectral slope and absorption band depth (or proxies thereof) the presence of diverse space weathering processes on asteroids adds significant ambiguity to the classification or curve match. Unless one makes the assumption that all asteroids exhibit the same degree of space weathering – which seems highly unlikely – any taxonomic classification or curve match is likely to be a function of both mineralogy and space weathering. Since the mechanisms of space weathering (other than for the Moon) are not well understood, it is often impossible to distinguish between color and spectral differences due to composition and those due to space weathering. This adds significant ambiguity to NEO classifications or characterizations based on curve matching techniques.

By contrast the methodology which utilizes diagnostic parameters such as band centers and relative band areas (band area ratios or BARs) is essentially unaffected by degrees of space weathering far in excess of that expected or observed on asteroid surfaces. This conclusion has either been stated explicitly or is evident from the work of virtually all asteroid space weathering studies whether from laboratory modeling or

from examining actual space weathered samples (e.g., Moroz *et al.* 1996, Hiroi and Sasaki 2001, Ueda *et al.* 2002, Strazzulla *et al.* 2005, Brunetto *et al.* 2006). Ueda (2002b) did report changes in the Band I center and the Band Area Ratio with space weathering, but a serious flaw in their methodology (*their computed spectral parameters do not match the laboratory spectral parameters measured by multiple investigators*) invalidates their conclusion. An example of the insensitivity of these diagnostic spectral parameters to space weathering is illustrated on Figure 4. No systematic shifts in band centers for lunar soil spectra are observed up to space weathering indices of 160 which corresponds to a mature lunar soil.

VNIR Characterization Procedures

The compositional / mineralogical characterization and albedo determination for an NEO includes five basic stages:

- i) Observation of the NEO and standard stars with at least NIR spectral coverage. The NEO should be observed multiple times to increase the signal-to-noise of the final spectra. Observations of a nearby solar-type standard star should be interspersed among the NEO observations. (Gaffey 2003, 2005; Gaffey *et al.* 2002)

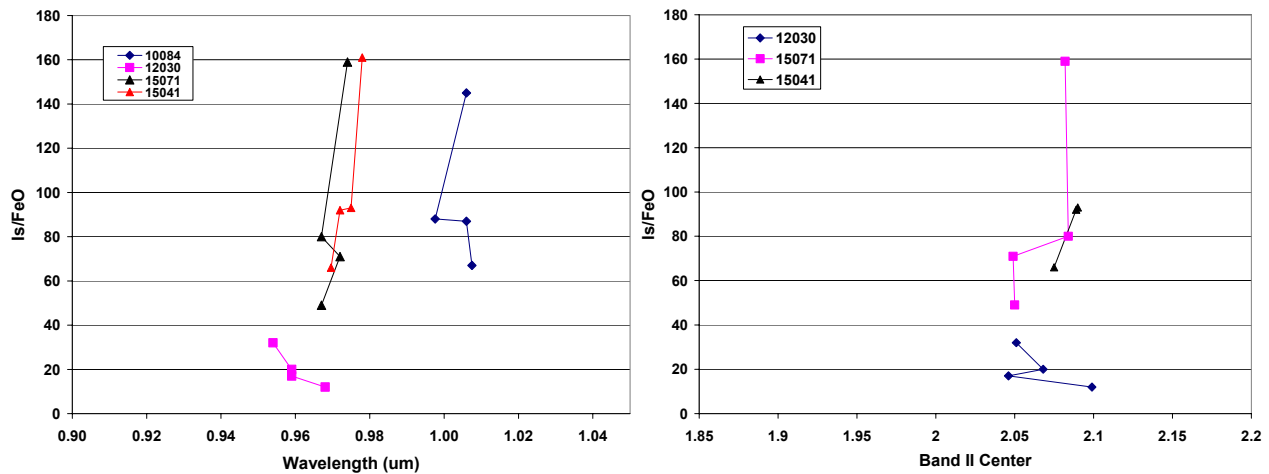


Figure 4 – Central wavelengths for Band I and Band II in the spectra of a subset of the lunar soil particle size separates described by Taylor *et al.* (2001). The vertical axis is the parameter I_S/FeO (ferromagnetic resonance intensity versus iron oxide content – See Morris 1976, 1978) which is a proxy for the degree of space weathering. No systematic shift in band positions occurs up to a space weathering index of 160. The space weathering index for asteroid surfaces is probably less than 20. The typical variations for any particular lunar sample set are $\pm 0.005 \mu m$ in Band I and $\pm 0.03 \mu m$ in Band II, ranges which are small compared to the range in these parameters among the suite of pyroxenes (~ 0.16 and $\sim 0.55 \mu m$, respectively). [Figures are from a paper in preparation by Gaffey.]

- ii) Reduction and calibration of the raw spectral data to remove the wavelength dependent effects of atmospheric absorptions, instrumental sensitivity, optical throughput and instrumental artifacts to produce a reflectance spectrum. This involves independent determination of the atmospheric extinction coefficients from the standard star observations in order to objectively correct the atmospheric absorptions. Average extinction coefficients for the observatory site or atmospheric transmission models that involve subjective corrections should not be used. Instrumental artifacts such as partial channel shift on the detector array must be corrected prior to calculation of the NEO/standard star ratio (reflectance). Post-reduction smoothing should not be used in lieu of preprocessing correction of such instrumental artifacts since that will produce spurious artifacts in the resultant spectra (e.g., Gaffey 2005, Gaffey *et al.* 2002)
- iii) Extraction of the diagnostic spectral parameters from the reflectance spectrum and identification of the mineralogy using established methodologies and interpretive calibrations (e.g., Gaffey *et al.* 2002). This should result in the identification of spectrally significant mineral species and determination of their mineral chemistries and relative abundances sufficient to identify or strongly constrain their meteoritic (or other) analogues.
- iv) Analysis of the mineralogy using principles derived from geology and meteorite studies to constrain the initial compositions of the original parent body and its geologic history and processes. This allows provides strong constraints on the intrinsic density and strength of the material comprising the NEO.

v) Determination of the albedo of NEOs exhibiting an excess flux due to thermal emission beyond $\sim 2.1 \mu\text{m}$ using thermal models (STM or other as appropriate) for the specific observing geometry and heliocentric distance of the NEO. **Although such albedo determinations are somewhat less robust than those derived from thermal infrared or polarimetric observations, they come at essentially no additional cost in dollars or observing time.** For NEOs which do not exhibit an excess flux, thermal models are used to place a lower limit on the albedo. For higher albedo NEOs where no thermal excess is observed, the mineralogical characterization can be used to estimate a plausible albedo. Based on our own experience, albedos can be determined for at least a third and as much as a half of the NEOs observed. Moreover, those for which excess fluxes cannot be detected are often strongly featured mafic silicate assemblages. The mineralogy and meteoritic analogs derived from the analysis of those spectra allow useful estimation of the albedos.

Determinations of NEO Sizes and Strengths

NIR spectra can be used to compute the sizes (diameters) for most NEOs and estimate the strengths for a subset of the NEOs.

vi) For those low albedo NEOs where NIR spectra provide a direct determination of albedo, all that is needed to compute a size (area) is a visual magnitude. In most cases, the visual magnitudes (commonly B or V filter) are obtained by a number of photometric observers including both professionals and amateurs. It is a relatively simple process in most cases to extrapolate the observed magnitudes to the time of the NIR observations. With a V or B magnitude and an albedo and the known observational geometry (heliocentric and geocentric distances and the phase angle), it's a simple calculation

to derive the effective cross-sectional area and hence mean diameter. If the photometric observations produced a lightcurve, the equatorial axial ratio can be derived, and if the NEO was observed at a variety of geometries, the triaxial figure can be estimated.

vii) For the subset of NEO ($\sim 1/6^{\text{th}}$) which are binary objects, masses can be derived using Kepler's 3rd Law if the distances between the components can be measured by direct imaging (e.g., adaptive optics, radar, interferometers) and the orbital period determined (e.g. lightcurve, direct imaging). Using the sizes (mean diameter, biaxial or triaxial ellipsoid shapes), the volume of the NEO can be computed and its bulk density (mass / volume) determined. If the bulk density is substantially less than the intrinsic density of the material which makes up the NEO, then it is most probable that the object is a porous rubble pile with essentially zero physical strength. Conversely, if the bulk and intrinsic densities are similar, the body is probably a relatively strong intact body or is composed mostly of a few large relatively strong intact fragments.

viii) If the NEO is a rapidly rotating body and the spectrum is consistent with a dominant metal component, then one can reasonably infer that it is a very strong metallic body.

Instrumentation Requirements

Existing instrumentation such as the SpeX instrument at the NASA Infrared Telescope Facility (IRTF) at Mauna Kea Observatory already have the capability of obtaining the needed NIR spectra for a significant fraction of the NEO and PHA populations (see white paper by Tokunaga *et al.*). Addition of a visual spectrograph (e.g., a CCD array detector $\sim 0.4\text{-}1.0 \mu\text{m}$) to the SpeX instrument or in parallel with it would extend coverage to the VNIR interval, which would provide additional constraints on mineralogical

characterizations. A high altitude site such as Mauna Kea greatly improves the ability to obtain continuous spectral coverage through the telluric water vapor absorption features. This is critical for detailed mineralogical characterizations.

Conclusions

Analysis of the diagnostic spectral parameters of low resolution ($\lambda/\Delta\lambda \sim 100$ -200) NIR (~ 0.7 -2.5 μm) spectra provides a sensitive and robust means of remotely characterizing a representative sample of NEOs and of identifying targets for subsequent focused ground-based and/or *in situ* investigation. Such spectral studies can identify the presence, abundance and compositions of the common mineral phases in most asteroidal assemblages and can identify the closest meteoritic analogs – or allow synthesis of appropriate analogs – as groundtruth samples.

Mineralogical characterizations and albedo determinations from NIR spectra provide a proven and cost effective basis for determining the sizes and strengths of NEOs, parameters which are critical to estimating the hazard potential of NEOs and to evaluating proposed mitigation strategies.

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