Characterizing Near Earth Asteroids: New Methods to Constrain Results from Simple Thermal Models Using IRTF SpeX Observations

Abstract

Near-Earth Asteroids (NEAs) are a critical testbed for many aspects of solar system science by nature of their proximity to Earth. Investigations into planet formation, asteroid dynamics, and planetary defense initiatives all rely on understanding key characteristics of NEAs such as their sizes, albedo distributions, and regolith properties. These important characteristics are typically inferred from simple thermal models that employ simplifying assumptions about an asteroid's shape and surface. These assumptions introduce potentially large errors in the characterization of NEA properties. However, the exact size and scope of these errors is currently unknown. We propose to carry out the first in-depth analysis of these errors in NEA simple thermal models using archival thermal spectra from the SpeX instrument on the NASA Infrared Telescope Facility (IRTF). Using these thermal spectra, we will generate simple thermal models of NEAs, which will be compared to more direct measurements of NEA properties from radar observations and more complex thermophysical models. This study will place the first detailed constraints on the accuracy of NEA characteristics measured using simple thermal models. This proposed analysis will provide critical information about these model errors that is needed to make full use of NEA data from the next generation of asteroid survey missions. We will then be able to more accurately characterize the NEA population and better understand the solar system at large.

- **Science Justification**

Simple Thermal Models are a Primary Tool for Understanding NEAs

Near-Earth Asteroids (NEAs) are a critical testbed for many aspects of solar system science. Understanding NEA properties such as sizes, albedo distributions, and regolith properties is critical for investigations into many aspects of solar system science, such as planet formation, asteroid orbital dynamics, surface processes on airless bodies, and understanding our meteorite collection (Michel+ 2015). NEAs are excellent targets to study these phenomena due to their proximity to the Earth. Furthermore, accurately measuring the sizes of NEAs is pivotal for planetary defense initiatives – the area of study focused on preventing catastrophic asteroid impacts with the Earth (Morrison & Teller 1995). Our understanding of many key objects and processes within our solar system therefore requires accurate knowledge of NEA properties.

NEA properties can be measured or inferred from a wide variety of observational and modeling techniques. These include radar images, detailed thermophysical models, and simple thermal models. Radar images can provide a highly accurate size estimate without other information (Ostro 1985) and can be used to construct a detailed model of the asteroid's shape (Magri+ 2007). These shape models can then be coupled with thermal observations to measure other physical properties of the asteroid with high accuracy using detailed thermophysical models (Marshall+ 2018, Howell+ 2018). However, one of the most commonly used methods is simple thermal models. These models are generally favored because they require little data and are computationally fast (Harris 1998, Howell+ 2018). These models can be run in seconds. compared to hours for more complex thermophysical models. Thus, simple thermal models and their results are an extremely important method for obtaining NEA properties.

However, simple thermal models can introduce potentially large errors into the characterization of NEA properties, because they employ simplifying assumptions about an asteroid's size and shape. Troublingly, the exact size and scope of these errors is currently unknown! Furthermore, with the recent collapse of the Arecibo Telescope restricting access to high resolution radar measurements of NEAs, and the advent of new survey missions like NEOSurveyor and LSST, simple thermal models will be increasingly relied upon to understand NEAs. It is therefore imperative to constrain the errors inherent in these models.

We propose to carry out the first in-depth analysis of the errors in NEA simple thermal models by using archival IRTF SpeX thermal spectra to generate simple thermal models of NEAs. The results of these models will then be compared to existing measurements of NEA properties, such as highly accurate radar sizes, to quantify the accuracy of the models. Constraining the errors of simple thermal models in this way will allow us to quantify the accuracy of the resulting NEA properties for the first time. This proposed program directly contributes to NASA's Planetary Science goals to "Explore and observe objects in the solar system" and "Identify and characterize objects in the solar system that pose threats to Earth."

The Scope of Errors in NEA Characterization Introduced by Simple Thermal Models is Unknown!

Simple thermal models employ a number of assumptions about the asteroids they are modeling, including a spherical shape for the asteroid, equatorial illumination, and an equatorial viewpoint (Lebofsky & Spencer 1989, Harris 1998). As a result of these assumptions, the models produce errors in the inferred measurements of asteroid properties. These errors are likely to be even more pronounced on smaller, more irregular shaped objects for which the model assumptions are violated. For example, recent work has shown that there are inconsistencies between asteroid sizes derived with simple thermal models and sizes measured via other methods (Masiero+ 2019). However, the exact size and scope of these errors is currently unknown. Because these models are widely used, our current knowledge of NEA physical properties is heavily skewed by these errors (Figure 1)!

In the upcoming era of large survey telescopes, quantifying these errors will be *imperative* to accurately understand the NEA population. Surveys such as LSST and NEOSurveyor will produce so much data that it will *require* the use of simple thermal models to analyze. This is because the time required for more advanced modeling techniques will be prohibitively large. Therefore, without in-depth analysis that determines the size and scope of errors in simple thermal models, our databases will soon be littered with inaccurate measurements of NEA properties. *This proposal will enable the first quantification of the size and scope of errors in simple thermal models, enabling a more accurate understanding of NEA properties as we move into the era of big data astronomy.*

NEA Thermal Spectra are Required to Infer NEA Properties using Simple Thermal Models

Analyzing the errors in NEA properties inferred from simple thermal models requires comparing the values inferred from simple thermal models to existing measurements with known uncertainties. Therefore, we must select for our analysis NEAs with existing direct measurements of their key properties. Simple thermal models are forward models, and so inferring the properties of NEAs using these models requires comparing modeled thermal spectra to real relative reflectance spectra of the NEAs. Specifically, we require reflectance spectra of target NEAs that span the region from ~1-microns to ~4-microns. This ensures that the data capture the "thermal upturn" region, where thermal emission begins to dominate reflected light, through the 3-micron water band (Howell+ 2018), as this is the wavelength region across which simple thermal models generate their modeled spectra. Thus, such spectra will allow us to infer the properties of targeted NEAs using simple thermal models.

Archival data generated by the SpeX instrument on the NASA IRTF is ideal for obtaining the type of spectra we require. Using the Prism (0.8-2.5 microns) and LXD (2.2-5.2 microns) modes, SpeX operates across the wavelength range we require (Rayner+ 2013). Via private communication, we have access to SpeX spectra of ~100 NEAs, more than 90% of which have existing radar size measurements. Furthermore, we have already carried out the analysis described here for the single NEA, 1998 QE2. We successfully used a simple thermal model to constrain 1998 QE2's albedo and thermal inertia (Figure 2) and measured the error in inferred size relative to radar-derived measurements (Springmann+ 2014). This test case shows that our proposed approach is feasible and will be easily applicable to the ~100 NEAs for which we have archival data. Expanding our analysis to all available NEA targets will provide a more complete picture of the scope of simple thermal model errors.

Comparing Simple Thermal Model Results to Direct Measurements of NEA Properties will Constrain Model Errors

We propose to quantify, for the first time, the size and scope of errors in NEA properties inferred from simple thermal models. This will be done by comparing values inferred using simple thermal models to values measured more directly. For example, radar derived diameters of NEAs are highly accurate (Ostro 1985). Thus, by comparing the diameter of an NEA as measured by radar to the diameter as inferred from a simple thermal model, the error in the simple thermal model result can be quantified. Repeating this analysis for different NEA characteristics, such as diameter, albedo, and thermal inertia, for a wide variety of NEAs, will thus give us an accurate description of the size and scope of simple thermal model errors.

This process will be done object by object for all ~100 NEAs in our archival thermal spectra data set. For each object, simple thermal models will be fit to the archival thermal data, producing inferred albedos, thermal inertias, and diameters for each object. These inferred values will then be compared to existing radar size measurements, the results of more complex thermophysical models, and results from spacecraft encounters, when available. (Arecibo radar observations are available for >90% of our ~100 NEAs and published results of more complex thermophysical models and spacecraft encounters are available for ~50% of these NEAs). These comparisons will yield a quantification of the errors in the simple thermal model results for each NEA analyzed. Since our data set represents a wide variety of NEA attributes, such as sizes, shapes, and taxonomic types, we will then be able to describe how these different NEA attributes affect the size and scope of simple thermal model errors. For example, we will be able to assess how different asteroid taxonomic types affect the results of these simple thermal models. *The final data product of this work will be a data set that quantifies, for a given NEA attribute (e.g. taxonomic type), the error induced in a simple thermal model of an asteroid with that attribute.* Our method is summarized in Figure 3.

The data set produced by this work will allow us to understand the errors of simple thermal model results. Since simple thermal models are widely used to understand NEA properties, this work will improve our overall understanding of the NEA population. Simple thermal models will also be heavily relied upon to interpret data from upcoming large surveys such as LSST and NEOSurveyor. Thus, this work will allow us to accurately analyze this data. This is not possible without performing the analysis proposed here.

Constraining the Errors in Simple Thermal Models Will Allow for More Accurate Analysis of Future Asteroid Data

By placing constraints on the errors of simple thermal model results, we will be able to make better use of these models in the future. Simple thermal models are often used when faced with limited time for analysis, as will be the case with the sheer volume of data returned from future survey missions. Thus, this proposed work will allow us to make more accurate determinations of NEA properties in the era of big data astronomy. Furthermore, a better understanding of NEA properties will directly contribute to a better understanding of planet formation, orbital dynamics, meteorites, and planetary defense. In this way, our proposed program addresses NASA's Planetary Science goals to "Explore and observe objects in the solar system" and "Identify and characterize objects in the solar system that pose threats to Earth."

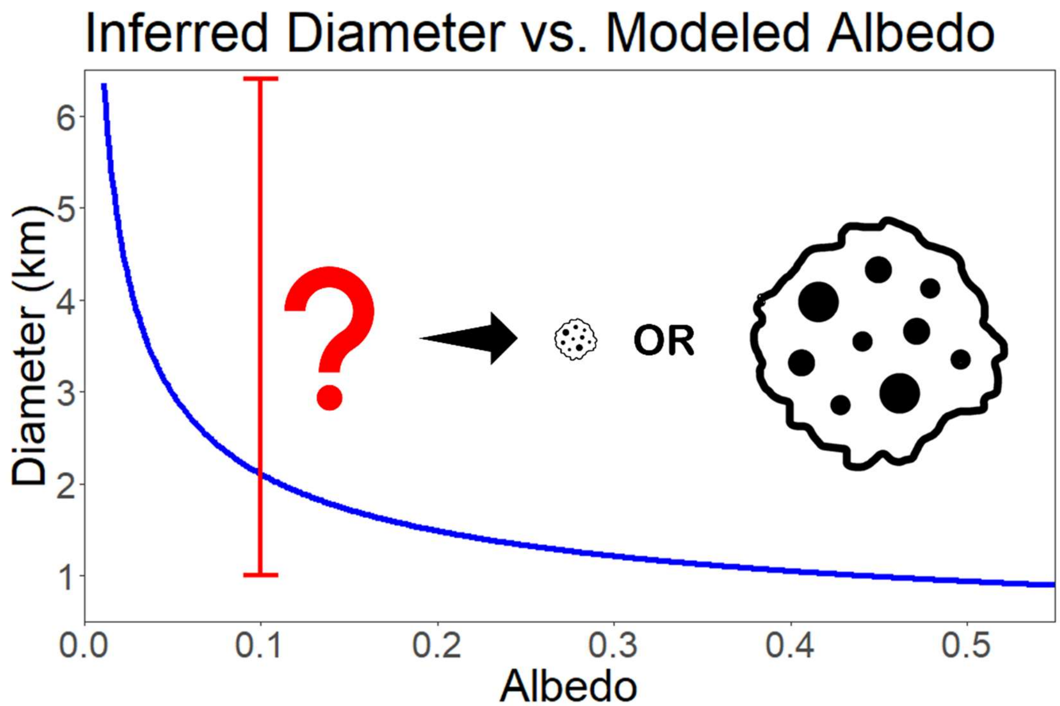

Figure 1: Simple thermal models often return wide ranges of NEA albedos due to the limitations they employ. Since NEA diameters can be derived as a simple function of albedo (Pravec & Harris 2007), these albedo ranges translate to huge uncertainties in inferred NEA sizes. This plot illustrates this relationship by showing diameter as a function of albedo (blue line). The red error bar shows how an albedo range of 0 to 0.5 translates to a large uncertainty in NEA diameter. This albedo range is typical for some simple thermal models. A to-scale representation of these size differences is also shown. *Our proposed, in-depth analysis to constrain errors of NEA properties derived with simple thermal models will tighten these constraints.*

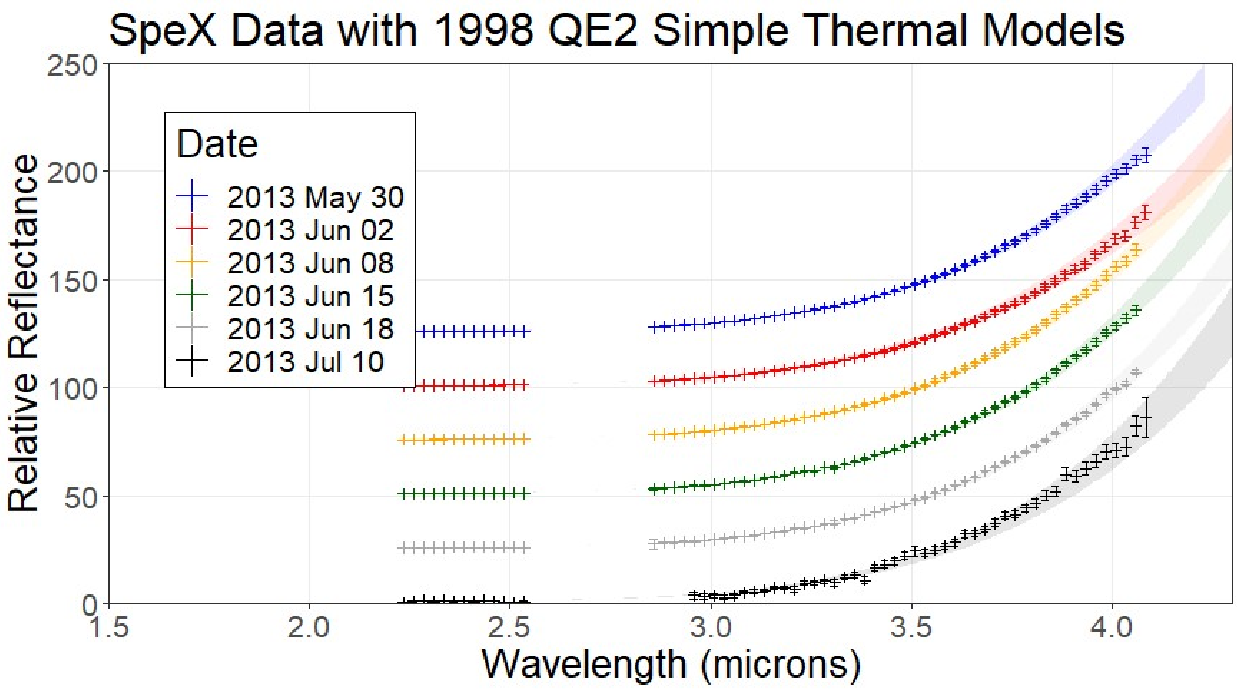

Figure 2: Relative reflectance of the NEA 1998 QE2 as a function of wavelength. We plot the SpeX data (crosses) alongside the ranges of best fit models from our simple thermal model (shaded regions). Each color is a different night of SpeX observations. The spectra are offset for clarity. We infer the properties of 1998 QE2 by finding values of albedo and thermal inertia that produce modeled spectra that match the data. For 1998 QE2, we infer an albedo of 0.05 to 0.08 and thermal inertia of 0 to 240 J m^{-2} $s^{-1/2}$ K^{-1}. Depending on the absolute magnitude value used, this albedo range can translate to diameters ranging from 1.6 to 3.5 km. Thus, these diameters have errors of up to 50% relative to the radar-derived measurement of 3.3 km (Springmann+ 2014). *Thermal spectra of NEAs will therefore allow us to quantify the errors in the properties of other NEAs inferred from simple thermal models.*

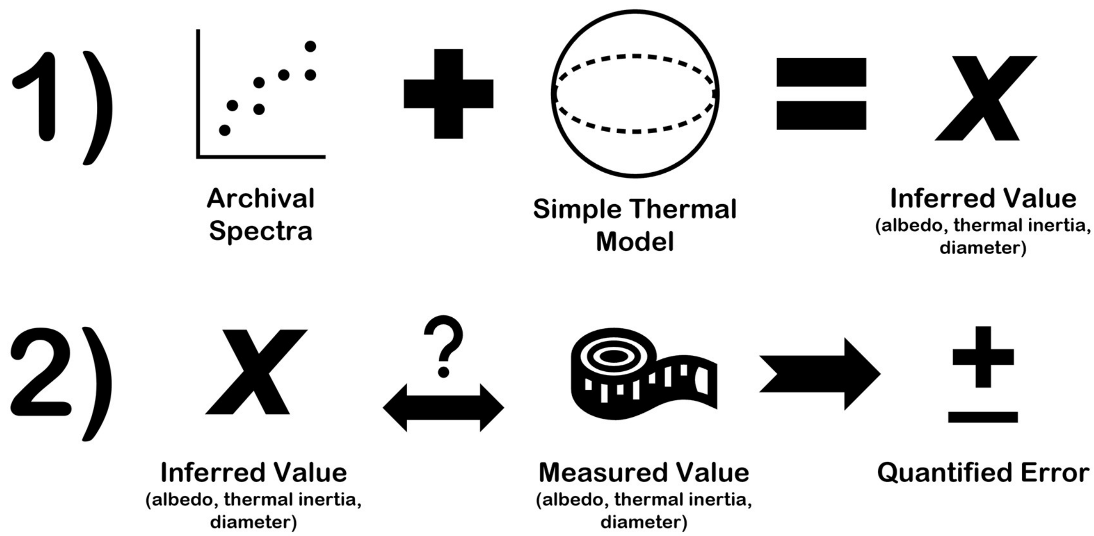

Figure 3: A pictorial summary of our proposed method. First, a simple thermal model is fit to the archival SpeX thermal spectra for each NEA. This produces inferred values of the albedo, thermal inertia, and diameter of the object. Second, the inferred values are compared to existing measurements from radar data, complex thermophysical models, or spacecraft encounters. This comparison results in a quantification of the error of the inferred value. *Repeating this analysis for all ~100 NEAs in our data set will show how different NEA attributes (e.g. taxonomic type) affect the size and scope of errors in simple thermal model results.*

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