**Motivation:** Thermal inertia estimates for near-Earth asteroids (NEAs) are paramount to upcoming asteroid sample-return missions such as NASA’s OSIRIS-REx, JAXA’s Hayabusa-2, and the proposed MarcoPolo-R of the European Space Agency, all three of which target carbonaceous asteroids. Additionally, these estimates build a foundation for the possibility of sending humans to asteroid surfaces in the near future. Specifically, asteroids with thermal inertias of <500 J m$^2$s$^{-0.5}$K$^{-1}$ likely support fine-grained regolith, the presence of which can be a significant factor in mission planning. As a result, more data are needed to properly characterize and understand the surface characteristics and compositions of NEAs.

The goal of the present work is to estimate thermal inertia values, albedos, and diameters for four NEAs, thereby adding to the small amount of existing thermal inertia data for NEAs. However, these thermal inertia estimates are preliminary and require more testing to ensure their accuracy. These estimates are derived from thermal infrared data from the Spitzer Space Telescope, and we hypothesize that these objects will have high thermal inertias because of their small size. Consequently, understanding the surface characteristics of these celestial objects is a powerful element that can provide insight into asteroid surface formation, evolution, and even composition. Analyzing NEAs may also provide important information for future spacecraft missions in our Solar System.

**Introduction:** NEAs comprise a group of asteroids that maintain stable orbits that bring them within 0.938 to 1.3 AU from the sun [1]. These objects are within close proximity to Earth’s orbit, which presents ample opportunity to study their surface characteristics, composition, and dynamical behavior. Many NEAs have been discovered, but very few have been characterized and studied in detail. Additionally, NEAs’ close distance to Earth presents another motivation for their study, in order to assess impact hazard and in understand how to avoid possible future asteroid impacts.

NEAs are thought to have originated from the main belt, which is a collection of asteroids that lie between the orbits of Mars and Jupiter. It is believed that collisions in the main belt have produced asteroid fragments that migrated into orbital resonances because of the Yarkovsky effect, and are then perturbed into near-Earth space. The Yarkovsky effect arises from the unequal emission of thermal radiation across the asteroid’s surface and can slowly change the asteroid’s orbit [2].

To study and quantify asteroid surface characteristics, we estimate a thermal inertia value for each object. Thermal inertia is given by the equation, $\Gamma = \sqrt{\rho kc}$ where the variables of density ($\rho$), thermal conductivity (k), and specific heat (c) of a body are related to the resistance of the surface to changes in temperature ($\Gamma$) [e.g., 3]. Thermal inertia can be used to infer the presence of a regolith of fine dust grains (or larger components) on an asteroid surface. This value also provides insight into the regolith depth, particle size, rock abundance, and occurrence of exposed rocks and boulders within the surface. For illustration, the Moon’s regolith has a low $\Gamma$ value of 50 SI units (J m$^2$s$^{-0.5}$K$^{-1}$), coarse sands are about 400, and normal bedrock is 2500 [3].

**Observations/Data Reduction:** The observations analyzed here were made in July of 2004, November and March of 2005, and April 2006 using NASA’s Spitzer Space Telescope. Spitzer was launched on August 25, 2003 and was sent into an Earth-trailing orbit and has since then collected valuable data in the infrared spectral range [4]. However, the Spitzer Space Telescope is no longer operable in the thermal infrared because it has run out of liquid helium to cool its instrumentation. While still cooled, Spitzer’s onboard InfraRed Spectrograph (IRS) instrument was used to collect thermal infrared data in the 5.2 to 38 $\mu$m spectral range for each object. These measurements were taken in Spitzer’s low resolution mode, where the full spectral coverage is segmented into four parts [5]. Standard calibration corrections (e.g., flats, darks) are applied by the Spitzer Science Center in their automated data reduction pipeline. We subtract background emission and extract into one-dimensional spectra. Different wavelength intervals of each spectrum are then combined and properly scaled together.

**Thermal Modeling:** Thermal inertia values for an asteroid surface can be computed from infrared observations that cover a range of wavelengths. As an asteroid spins on its axis, the side facing the sun receives infrared radiation and heats up while the side facing away from the sun cools. The thermal flux seen by an observer contains information on the temperature distribution of the visible hemisphere. We model the temperature distribution, varying appropriate parameters (e.g., thermal inertia) to find a temperature distribution that produces a model disk-integrated thermal flux spectrum that matches the observation. The temperature distribution of the surface also depends on the asteroid’s shape,
inclination, and spin rate which all must be determined and accounted for.

The relatively simple near-Earth asteroid thermal model (NEATM), outlined by [6], uses a variable called the beaming parameter, $\eta$, which can be adjusted to fit the model thermal curve. This model can provide good fits to NEAs as well as other asteroids throughout the Solar System. However, $\eta$ does not have a unique physical interpretation, but rather encapsulates the effects of several properties (e.g., thermal inertia, surface roughness). We used the NEATM to compute thermal models that solve for each asteroid’s radius (km), albedo (pv), and optimal beaming parameter ($\eta$). Each asteroid’s thermal data, absolute magnitude, rotational period, heliocentric distance, Sun-Target-Observer angle, and other spatial characteristics are fed into the NEATM to calculate the desired parameters.

Our real goal, however, was to estimate a thermal inertia value for each object. A thermophysical model allows us to calculate thermal inertia by incorporating the process of heat conduction into the interior of the asteroid during the day, storage, and the emission of heat during the night. The model uses the position of the asteroid’s spin axis relative to the location of the Spitzer Space Telescope and the angle between the asteroid and the sun. For example, if the asteroid’s spin axis were pointed directly at the sun, there would be little variation in thermal emission across the object’s surface. If the position of the sun is perpendicular to the spin axis of the asteroid (i.e., above the equator), then there will be increased night side thermal emission from the object and the variation in thermal emission across the surface would increase [7]. These effects are important to consider when using the thermophysical model to estimate a thermal inertia for an object.

Results/Discussion: A modeled thermal curve of asteroid 1580 Betulia using the NEATM is shown in figure 1.

![Figure 1](1580 Betulia.png)  
**Figure 1.** Thermal Emission Spectra for 1580 Betulia. We estimate a low albedo (pv) and beaming parameter ($\eta$).

In the emission spectrum, the blue curve shows extracted spectra from the four IRS modules with no scaling. The black curve shows the final spectral flux after scaling of the four modules relative to each other, and the red curve is the NEATM fit to the scaled data. Also displayed are the calculated albedos (pv), radii (km), and optimal beaming parameters ($\eta$) for each object. A table of these values are also displayed in table 1 for all four of the observed asteroids.

<table>
<thead>
<tr>
<th>Asteroid</th>
<th>Diameter (km)</th>
<th>Albedo (pv)</th>
<th>Beaming Parameter ($\eta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1620 Geographos</td>
<td>2.06 ± 0.07</td>
<td>0.384 ± 0.069</td>
<td>1.31</td>
</tr>
<tr>
<td>1580 Betulia</td>
<td>4.32 ± 0.10</td>
<td>0.086 ± 0.002</td>
<td>0.84</td>
</tr>
<tr>
<td>1580 Betulia</td>
<td>3.82 ± 0.58</td>
<td>0.11 ± 0.04</td>
<td>1.09</td>
</tr>
<tr>
<td>1580 Toro</td>
<td>3.86 ± 0.07</td>
<td>0.327 ± 0.083</td>
<td>1.86</td>
</tr>
<tr>
<td>1580 Syphus</td>
<td>8.6 ± 0.015</td>
<td>0.247 ± 0.026</td>
<td>1.04</td>
</tr>
</tbody>
</table>

*Table 1. Table of each asteroid’s calculated diameter, albedo, and optimal beaming parameter using the NEATM.*

We run the thermophysical model over a grid of thermal inertia values. For each value of thermal inertia, the model varies the object’s size to find the lowest possible chi square statistic for that estimate. Figure 2 shows asteroid 1620 Geographos may have a thermal inertia of around 100. These thermal inertia estimates require further testing and review to ensure their accuracy. We will present thermal inertia values for all four NEAs.

![Figure 2](1620 Geographos.png)  
**Figure 2.** Plot showing thermal inertia vs. the calculated chi square statistic for 1620 Geographos. The lowest chi square value occurs at a thermal inertia of 100.