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THERMAL AND SPIN PROPERTIES OF NEAR-EARTH OBJECTS: CONSTRAINTS FROM NEXT-GENERATION INFRARED SURVEYS

T. S. Statler(1), T. Grav(2), J. Masiero(3), C. R. Nugent(4), and A. K. Mainzer(5)
(1)*Astrophysical Institute, Ohio University, Athens OH 45701, USA,*
Astronomy Dept., University of Maryland, College Park MD 20742 USA, and
NASA Headquarters, Washington DC 20546,USA;
(2)*Planetary Science Institute, Tucson AZ 85719, USA;*
(3)(5)*Jet Propulsion Laboratory, Pasadena CA, USA;*
(4)*Infrared Processing and Analysis Center, Caltech, Pasadena CA 91125, USA;*

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Extended Abstract— The thermal inertias (denoted Γ) of small-body surfaces are important indicators of their material properties. Measurements of thermal inertia can, in principle, distinguish between regolithic ($\Gamma \sim 10^{1}$ Jm^{-2}s$^{-1/2}$K^{-1}), fractured ($\Gamma \sim 10^{2}$ Jm^{-2}s$^{-1/2}$K^{-1}), and monolithic ($\Gamma \sim 10^{3}$ Jm^{-2}s$^{-1/2}$K^{-1}) surfaces. When combined with rotation rates, the thermal inertias of fast-rotating objects can additionally yield constraints on cohesion in the surface layers. Surface mechanical and thermal properties are key inputs for calculations of both natural (e.g., Yarkovsky) and human-induced (e.g. kinetic impact) orbital changes. Hence, the determination of thermal inertias for different NEO sub-populations, as well as for individual PHAs, will be an important aspect of future characterization efforts.

In current practice, thermal inertias are obtained through detailed, targeted observations of individual bodies having well constrained shapes (e.g., Ali□Lagoa et al. 2014 A&A 561 A45, Mueller et al. 2014 A&A 566 A22, Emery et al. 2014 Icarus 234 17). Multiple observations, typically including optical light curves, radar, and thermal infrared, are required for robust and precise results. However, we show here that the next generation of space-based infrared NEO surveys offer the potential to measure, at least coarsely, thermal inertias for hundreds to thousands of objects, as well as simultaneously constrain their spin axis orientations, without the need for extensive optical or radar observations. This new information about the various NEO populations will give us the capability to do limited pre-characterization of potential impactors before discovery.

The unique aspects of next-generation IR surveys that distinguish them from previous survey and targeted observations are (1) the large number of objects that will be observed at many epochs, at many different positions around their orbits, and at many different elongation and phase angles; and (2) the sparse photometry at each epoch that will generally undersample the rotational light curves. As an archetype for such a survey we consider the plan for the proposed NEOCam mission (Mainzer 2006 AAS DPS 38th Mtg. Abstr. 45.09). We have carried out extensive simulations to determine what will be constrainable from the IR survey photometry when *no* shape model exists, and when only modest additional data—for instance, a single-night optical observation to pin down the rotation period—are available.

We simulate IR light curves for both idealized (spherical and ellipsoidal) and realistic (radar-derived) shapes, using the thermophysical code TACO (Statler 2009 Icarus 202 502). The code includes the effects of shadowing, self-illumination by reflected light, self-irradiation by emitted thermal IR, and 1-dimensional heat conduction into and out of the surface. Using simulations of the NEOCam survey (Mainzer et al. 2015 AJ in press, arXiv:1501/01063), we choose 8 specific NEO orbits (2 Atens, 2 Amors, 2 Apollos, and 2 Interior-to-Earths), for which the putative survey cadence generates >100 photometric data points in each band distributed over >10 epochs with distinct observing geometries. We refer to these 8 things as "objects" even though their physical parameters are arbitrary. The 8 objects comprise observations at a total of 292 epochs. Each object is computed with 13 different shapes: 1 sphere, 8 triaxial ellipsoids, and 4 shapes mimicking real objects—QuasiBennu, QuasiCastalia, QuasiEros, and QuasiKleopatra. The shapes are oriented with 12 different rotation poles, distributed uniformly over the celestial sphere. Finally, the surfaces are assigned 5 different values of Γ between 25 and 1600 Jm^{-2}s$^{-1/2}$K^{-1}, equally spaced in log Γ. This generates a library of $292\times13\times12\times5=227{,}760$ light curves in each of the two NEOCam bands (4 and 10 μm). Other parameters, for the results reported here, held fixed, as they are of lesser importance. The rotation period is set at $P = 2$ hr;

since all thermal effects depend only on the combination $\Gamma P^{-1/2}$, results are easily scaled to other values of P. The optical and IR reflectivity are Lambertian (isotropic) with a geometric albedo of 0.145, and the IR emission is also Lambertian with an emissivity of 0.9.

We then ask to what extent it is possible to constrain Γ, having no a priori knowledge of the shape. In the results reported here, we assume that the rotation period is known, either directly from the survey data or from optical follow-up. We pick one combination of object, shape, and rotation pole, and take the case with the middle value of thermal inertia (Γ = 200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$, for P = 2 hr) as the "true NEO". We do not try to simulate individual photometric measurements; instead, we assume that the multiple data points at each epoch will be used to determine the mean flux and the light curve amplitude in each band, with uncertainties σ_m and σ_a respectively (in magnitudes). Monte-Carlo simulations of randomly sampled light curves indicate that when the period is known, one can typically achieve $\sigma_a = 2.5\ \sigma_m$; so we parameterize the observational errors by σ_m, and simulate observations of the true NEO by computing the mean and amplitude at each epoch, and adding Gaussian noise. We fit the simulated data using objects from the light curve library, to check whether the correct parameters are recovered by the best-fit model and determine which incorrect models can be ruled out by the data. This process is then repeated, taking, in turn, each Γ = 200 $\mathrm{Jm^{-2}s^{-1/2}K^{-1}}$ object-shape-pole combination from the library as the true NEO, to obtain statistics on the strength of the constraints.

We examine three situations: (1) ellipsoidal NEOs fitted with ellipsoidal models, to test the fundamental limitations of the approach; (2) realistically-shaped NEOs fitted with ellipsoidal models, the likely situation for most observed objects in the survey; and (3) both ellipsoidal and realistic NEOs fitted exclusively with spherical models, anticipating a strong desire in the community to use this approach.

We find that, in general, meaningful constraints on thermal inertia, shape, and rotation pole are achievable when $\sigma_m < 0.1$ mag, fundamentally because these basic parameters govern how the surface temperature map is modulated around the orbit by seasonal variations in the incident solar flux. Because seasonal variations are key, rotation poles turn out to be particularly well constrained. With the resolution of our library, the sampled poles are separated by approximately 63°, and so we are unable with these results to accurately predict typical pole uncertainties. However, we find that for ellipsoidal NEOs nearly all of the incorrect poles in the library are ruled out at better than 2σ confidence in more than 90% of the trials when $\sigma_m < 0.1$ mag, and in more than 99% of the trials when $\sigma_m < 0.05$ mag. The exception is the antipodal pole, corresponding to the opposite sense of rotation, which can be ruled out only between 30% and 80% of the time over the same range of σ_m. For realistically shaped objects modeled with ellipsoids, the results are similar but the constraints are slightly weaker.

There is substantial covariance—which is to say, degeneracy—between thermal inertia and shape. A rounder object with higher Γ can masquerade as a more elongated object with lower Γ. In terms of the axis ratios b/a and c/a, the direction in shape space having the highest covariance with Γ corresponds approximately to $\Delta(c/a)/\Delta(b/a) = -2$. The sense of the effect is somewhat counterintuitive, and is driven primarily by how the mean flux is seasonally modulated, rather than the amplitude of the rotational light curve.

The simulations with ellipsoidal NEOs show that it is possible to distinguish intermediate values of thermal inertia from extreme regolithic or monolithic values with sufficiently good data. The extreme Γ values can be ruled out at 2σ confidence approximately half the time if $\sigma_m < 0.1$ mag, and more than 90% of the time if $\sigma_m < 0.05$ mag. For realistic asteroid shapes that are not too extreme, fitting with ellipsoidal models yields results are nearly as promising. For QuasiBennu and QuasiCastalia, the regolithic and monolithic values of Γ are ruled out in approximately 25% and 85% of trials for $\sigma_m < 0.1$ mag and $\sigma_m < 0.05$ mag, respectively.

In the cases of highly elongated shapes with substantial concavities, we find a similar potential for distinguishing fractured rock from monolithic rock or regolith, although we also see a bias toward spuriously low Γ. The mean Γ values of the best-fit ellipsoidal models fitted to QuasiEros and QuasiKleopatra are roughly half of the correct values. This bias is almost certainly related to shadowing that occurs in concavities, rather than to the elongation. Shadowing tends to increase the temperature contrast over the surface, which echoes the effects of decreasing thermal inertia. But this bias is not so large that it utterly defeats attempts to constrain Γ, indicating that robust results may still be obtained using ellipsoids to model non-ellipsoidal objects.

Finally, we find a comparable bias in the opposite direction when using strictly spherical models to fit non-ellipsoidal shapes. Because of the degeneracy between shape and thermal inertia discussed above, assuming a spherical model is almost guaranteed to overestimate Γ. This bias is typically a factor of ~ 2, and can amount to as much as a factor of 4 or more depending on shape.

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