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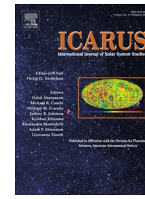

Near-infrared thermal emission from near-Earth asteroids: Aspect-dependent variability

Nicholas A. Moskovitz[a,c,1,*], David Polishook[b], Francesca E. DeMeo[c], Richard P. Binzel[c], Thomas Endicott[d], Bin Yang[e,f], Ellen S. Howell[g], Ronald J. Vervack, Jr.[h], Yanga R. Fernández[i]

[a] Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001 (U.S.A.)
[b] Department of Earth and Planetary Sciences, Weizmann Institute of Science, Rehovot 7610001 (Israel)
[c] Massachusetts Institute of Technology, Department of Earth, Atmospheric and Planetary Sciences, 77 Massachusetts Avenue, Cambridge, MA 02139 (U.S.A.)
[d] University of Massachusetts, Boston, 100 Morrissey Blvd., Boston, MA 02125 (U.S.A.)
[e] Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822 (U.S.A.)
[f] European Southern Observatory, Alonso de Cordova, 3107, Vitacura, Casilla 19001, Santiago de Chile (Chile)
[g] Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721, U.S.A.
[h] JHU/Applied Physics Lab, 11100 Johns Hopkins Road, Laurel MD 20723 (U.S.A.)
[i] University of Central Florida, Dept. of Physics, 4000 Central Florida Blvd. Orlando FL 32828 (U.S.A.)

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Here we explore a technique for constraining physical properties of near-Earth asteroids (NEAs) based on variability in thermal emission as a function of viewing aspect. We present case studies of the low albedo, near-Earth asteroids (285263) 1998 QE2 and (175706) 1996 FG3. The Near-Earth Asteroid Thermal Model (NEATM) is used to fit signatures of thermal emission in near-infrared (0.8 - 2.5 µm) spectral data. This analysis represents a systematic study of thermal variability in the near-IR *as a function of phase angle*. The observations of QE2 imply that carefully timed observations from multiple viewing geometries can be used to constrain physical properties like retrograde versus prograde pole orientation and thermal inertia. The FG3 results are more ambiguous with detected thermal variability possibly due to systematic issues with NEATM, an unexpected prograde rotation state, or a surface that is spectrally and thermally heterogenous. This study highlights the potential diagnostic importance of high phase angle thermal measurements on both sides of opposition. We find that the NEATM thermal beaming parameters derived from our near-IR data tend to be of order10's of percent higher than parameters from ensemble analyses of longer wavelength data sets. However, a systematic comparison of NEATM applied to data in different wavelength regimes is needed to understand whether this offset is simply a reflection of small number statistics or an intrinsic limitation of NEATM when applied to near-IR data. With the small sample presented here, it remains unclear whether NEATM modeling at near-IR wavelengths can robustly determine physical properties like pole orientation and thermal inertia.

1. Introduction

Obliquity (a scalar) or spin vector is a fundamental property of all celestial bodies. In the Solar System, spin vectors directly influence the efficiency in which the Yarkovsky and YORP effects (i.e. thermal radiation forces and torques) change the orbital and rotational properties of minor planets (Bottke et al., 2006; Rubincam, 2000; Vokrouhlicky et al., 2015). The Yarkovsky effect plays a key role in the dynamical transport of small asteroids from the Main Belt into the near-Earth population (Farinella and Vokrouhlický, 1999). The YORP effect directly influences rotation state and is frequently invoked to explain the formation of binary and multiple asteroid systems through rotational fission or mass shedding (Jacobson and Scheeres, 2011; Margot, 2002; Pravec, 2010; Scheeres, 2007; Walsh et al., 2008). Furthermore, spin states are a direct consequence of asteroid-asteroid impacts and thus trace collisional environments across dynamical populations (Paolicchi et al., 2002).

Despite the importance of spin vectors, only a few hundred out of three quarters of a million known asteroids have constrained

* Corresponding author.
E-mail address: nmosko@lowell.edu (N.A. Moskovitz).
[1] Observations conducted while at MIT, current affiliation is Lowell Observatory.

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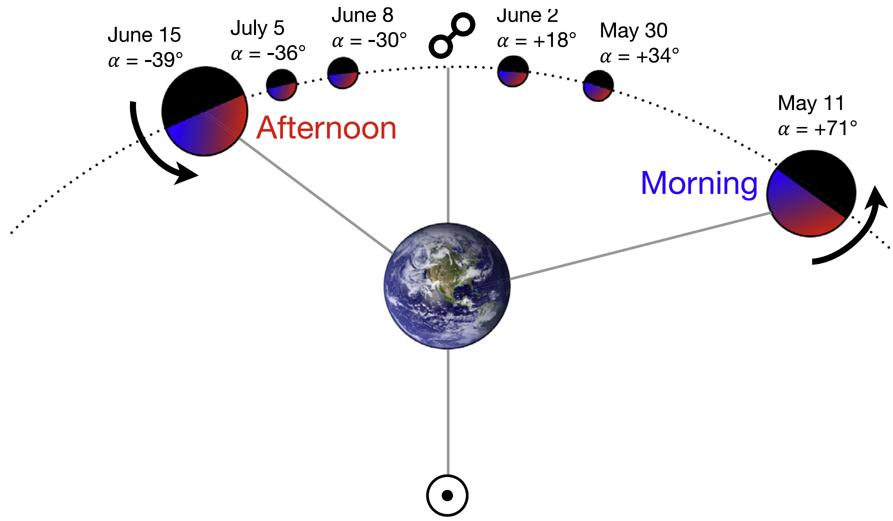

Fig. 1. Schematic of the opposition (☍) centered orbital longitude of 1998 QE2 during its 2013 apparition. The dates and corresponding solar phase angles (α, signed relative to opposition) are indicated for each of our observations. The asteroid cartoons are shaded to indicate illumination (black = nighttime hemisphere) and surface temperate distribution for a body with finite thermal inertia (blue = cold, red = hot). The predicted prograde rotation of the asteroid (Springmann, 2014) is indicated by the black arrows. The cartoons of the asteroid at maximal phase angles (+71° and −39°) are larger to emphasize the preferential viewing of cooler morning temperatures prior to opposition and warmer afternoon temperatures post-opposition. Note the phase angle actually decreased after the 15 June observation. Earth image credit: NASA/GSFC. (For interpretation of the references to color in this figure, refer to the web version of the article.)

pole orientations. This is a direct consequence of the many years or even decades required to constrain spin vectors through astrometric or photometric observations (e.g. Kaasalainen et al., 2002; Slivan, 2002; Lowry, 2007; Nugent et al., 2012). Analyses across shorter temporal baselines often suffer from retrograde-prograde degeneracies. Doppler delay radar imaging can determine shape and pole solutions, but requires sufficient sky motion during the observing window and is limited to the closest near-Earth and largest Main Belt asteroids (Ostro et al., 2002).

Here we focus on an alternate technique for constraining spin orientation, namely by monitoring thermal emission as a function of solar phase angle. This technique does not solve for the obliquity or specific spin vector, but can constrain retrograde versus prograde spin orientation. Measuring thermal emission from a body at multiple viewing geometries on either side of opposition can reveal differences in local morning versus afternoon temperature distributions across the surface of an asteroid (Fig. 1). The rotational sense of the body directly influences the local time and temperature distribution on the asteroid surface as perceived from Earth, particularly when observing at geometries of high phase angle. This afternoon-morning temperature dichotomy can observationally manifest as a difference in thermal emission. For the case depicted in Fig. 1, preferential viewing of the “cold” hemisphere before opposition and the “warm” hemisphere afterwards would be reversed if this object were in retrograde rotation. Therefore, variations in thermal flux on either side of opposition can serve to constrain pole orientation. Thermal observations across a range of phase angles is a standard method for determining asteroid thermal inertia (Delbo et al., 2015).

This technique, originally described (Matson, 1971) and pioneered in the 1970’s, has not been widely used to constrain pole orientation, but has seen some success. Morrison (1976) confirmed that the near-Earth asteroid 433 Eros is in a prograde rotation state based on enhanced 10- and 20-μm thermal emission prior to opposition, consistent with preferential viewing of local afternoon. Even though Eros’ pole only points 11° above the ecliptic (Zuber, 2000) its moderate orbital inclination (10.8°) and observations by Morrison (1976) at moderate to high solar phase angles (−41°, −24°, and +42°) ensured that the afternoon and morning sides of Eros were preferentially viewed prior to and after opposition respectively. Morrison (1977) and Hansen (1977) extended this technique to several large Main Belt asteroids. They were able to correctly predict prograde rotation for 1 Ceres (Johnson et al., 1983), 4 Vesta (Gehrels, 1967) and 19 Fortuna (Torppa, 2003), and a retrograde state for 10 Hygeia (Kaasalainen et al., 2002). However they did not correctly predict the retrograde rotation of 2 Pallas (Carry, 2010; Torppa, 2003). There are likely several reasons for this. First, the prediction for Pallas was tenuous anyways due to it having the fewest observations of the objects under investigation. Second, the standard thermal model used to derive physical properties (including pole orientation) assumed non-rotating spherical bodies. Third, the range of accessible phase angles for objects in the Main Belt is limited relative to near-Earth objects. Finally, the possibility of low surface thermal inertia for large (> 100 km) asteroids (e.g. Delbo et al., 2015) acts to dampen morning-afternoon temperature gradients. In light of these issues, it is impressive that these early investigations resulted in meaningful constraints on the rotation states of any of the targeted asteroids. Since these initial studies, the use of a morning-afternoon temperature dichotomy to inform pole orientation has only been discussed and applied in a few cases (e.g. Lebofsky, 1986; Harris et al., 2007; Muller, 2012). Note that this method is not sensitive to objects with poles aligned near to the line of sight, nor does it provide a measure of the object obliquity, instead it simply provides a means to constrain a prograde versus retrograde spin state.

Traditionally, the measurement of asteroid thermal emission and subsequent modeling of physical properties has relied on mid-infrared (3–25 μm) photometry. An asteroid thermo-physical model called SHERMAN has been developed for application to airless bodies of arbitrary shape and has primarily been applied to (though is not restricted to) observations at wavelengths between 2.5 - 4.0 μm (Howell, 2015). However, low albedo (< 10%) asteroids at small heliocentric distances (< 1.2 AU) have high enough surface temperatures that the Wien tail of their thermal emission profiles can be detected at near-infrared wavelengths (0.8 - 2.5 μm). At such short wavelengths the measured signal is a combination of solar reflectance and thermal emission. This thermal excess or thermal tail can be modeled to retrieve surface temperature and albedo (Reddy et al., 2009; 2012; Rivkin et al., 2005). However, models of this excess from normalized reflectance spec-