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*

^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.*

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¹ Observations conducted while at MIT, current affiliation is Lowell Observatory.

Proposed Running Head: NEA Thermal Emission

Please send Editorial Correspondence to:

Nicholas A. Moskovitz

Lowell Observatory

1400 West Mars Hill Road

Flagstaff, AZ 86001, USA.

Email: nmosko@lowell.edu

Phone: (928) 779-5468

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 (Rubincam, 2000; Bottke et al., 2006; 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 & 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 (Margot et al., 2002; Scheeres, 2007; Walsh et al., 2008; Pravec et al., 2010; Jacobson & Scheeres, 2011). 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 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 et al., 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.

26 This technique does not solve for the obliquity or specific spin vector, but
 27 can constrain retrograde versus prograde spin orientation. Measuring thermal
 28 emission from a body at multiple viewing geometries on either side of oppo-
 29 sition can reveal differences in local morning versus afternoon temperature
 30 distributions across the surface of an asteroid (Figure 1). The rotational sense
 31 of the body directly influences the local time and temperature distribution
 32 on the asteroid surface as perceived from Earth, particularly when observing
 33 at geometries of high phase angle. This afternoon-morning temperature di-
 34 chotomy can observationally manifest as a difference in thermal emission. For
 35 the case depicted in Figure 1, preferential viewing of the “cold” hemisphere
 36 before opposition and the “warm” hemisphere afterwards would be reversed if
 37 this object were in retrograde rotation. Therefore, variations in thermal flux on
 38 either side of opposition can serve to constrain pole orientation. Thermal ob-
 39 servations across a range of phase angles is a standard method for determining
 40 asteroid thermal inertia (Delbo et al, 2015).

41 This technique, originally described (Matson, 1971) and pioneered in the
 42 1970’s, has not been widely used to constrain pole orientation, but has seen
 43 some success. Morrison (1976) confirmed that the near-Earth asteroid 433
 44 Eros is in a prograde rotation state based on enhanced 10- and 20- μm ther-
 45 mal emission prior to opposition, consistent with preferential viewing of local
 46 afternoon. Even though Eros’ pole only points 11° above the ecliptic (Zuber et
 47 al., 2000) its moderate orbital inclination (10.8°) and observations by Morrison
 48 (1976) at moderate to high solar phase angles (-41° , -24° , and $+42^\circ$) ensured
 49 that the afternoon and morning sides of Eros were preferentially viewed prior
 50 to and after opposition respectively. Morrison (1977) and Hansen (1977) ex-
 51 tended this technique to several large Main Belt asteroids. They were able
 52 to correctly predict prograde rotation for 1 Ceres (Johnson et al., 1983), 4

Fig. 1. Schematic of the opposition ($\circ$) 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 temperature distribution for a body with finite thermal inertia (blue = cold, red = hot). The predicted prograde rotation of the asteroid (Springmann et al., 2014) is indicated by the black arrows. The cartoons of the asteroid at maximal phase angles ($+71^\circ$ 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 June 15 observation. Earth image credit: NASA/GSFC.

53 Vesta (Gehrels, 1967) and 19 Fortuna (Torppa et al., 2003), and a retrograde
54 state for 10 Hygeia (Kaasalainen et al., 2002). However they did not cor-
55 rectly predict the retrograde rotation of 2 Pallas (Torppa et al., 2003; Carry
56 et al., 2010). There are likely several reasons for this. First, the prediction
57 for Pallas was tenuous anyways due to it having the fewest observations of
58 the objects under investigation. Second, the standard thermal model used to
59 derive physical properties (including pole orientation) assumed non-rotating
60 spherical bodies. Third, the range of accessible phase angles for objects in the
61 Main Belt is limited relative to near-Earth objects. Finally, the possibility of
62 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 et al., 1986; Harris et al., 2007; Muller et al., 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 et al., 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 (Rivkin et al., 2005; Reddy et al., 2009, 2012). However, models of this excess from normalized reflectance spectra are not directly sensitive to diameter because such data are not flux calibrated.

Here we present case studies of the near-Earth asteroids (285263) 1998 QE2 (§3) and (175706) 1996 FG3 (§4) based on observations during apparitions favorable to the detection of phase-dependent thermal variability. This analysis

89 represents the first systematic study of thermal variability in the near-IR K-
90 band as a function of phase angle.

91 **2 Observations and Thermal Modeling**

92 Both 1998 QE2 and 1996 FG3 have low geometric albedos of about 3% and
93 4% respectively (Trilling et al., 2010; Wolters et al., 2011), and thus display
94 significant thermal emission in the near-infrared when they are at heliocentric
95 distances of ~ 1 AU. We present near-infrared spectra of 1998 QE2 taken
96 between May and July of 2013 and of 1996 FG3 taken during apparitions
97 in 2009 and 2011 (Tables 1 and 2). All data analyzed here were obtained
98 with SpeX at NASA’s Infrared Telescope Facility, which was configured in its
99 low resolution ($R \sim 100$) prism mode with a $0.8''$ slit (Rayner et al., 2003).
100 All observations were conducted with the telescope operating in a standard
101 ABBA nod pattern. Commonly-used solar analogs (DeMeo et al., 2009) were
102 observed to correct for telluric absorption and to remove the solar contribution
103 from the measured reflectance. Reduction protocols followed Moskovitz et al.
104 (2013) and DeMeo et al. (2009).

105

Observation Date (UT)	V [mag]	r [AU]	Δ [AU]	α [deg]	$\eta_{3\%}$	$\eta_{6\%}$	$\eta_{1\%}$
2013 May 11	15.4	1.045	0.129	+71.0	1.56 ± 0.05	1.29	2.03
2013 May 30	11.8	1.047	0.040	+34.0	1.18 ± 0.02	0.97	1.57
2013 June 2	11.4	1.052	0.040	+17.9	1.08 ± 0.03	0.89	1.45
2013 June 8	12.7	1.067	0.061	-30.4	1.11 ± 0.02	0.91	1.48
2013 June 15	14.0	1.091	0.099	-38.8	1.16 ± 0.03	0.95	1.54
2013 July 5	15.9	1.189	0.223	-35.9	1.10 ± 0.03	0.91	1.45

Table 1

Summary of (285263) 1998 QE2 observations and best-fit NEATM thermal beaming parameter (η) values for the full range of possible albedos from 1-6%.

Observation Date (UT)	V [mag]	r [AU]	Δ [AU]	α [deg]	$\eta_{3.9\%}$	$\eta_{5.1\%}$	$\eta_{2.7\%}$	Mutual Event?
2009 March 30	16.2	1.223	0.227	+8.3	1.35 ± 0.05	1.27	1.48	No
2009 April 27	16.7	1.081	0.159	+58.4	1.9 ± 0.1	1.78	2.07	Secondary occulted by primary
2011 December 1	15.6	1.050	0.108	-51.5	1.35 ± 0.05	1.28	1.50	Secondary occulted by primary
2011 December 30	16.4	1.203	0.228	+14.0	1.12 ± 0.03	1.05	1.23	Primary eclipsed and occulted by secondary

Table 2

Summary of (175706) 1996 FG3 observations and best-fit NEATM η values for the full range of possible albedos from 2.7-5.1%.

107 We model the thermal tails of our targets with the near-Earth asteroid thermal
 108 model (NEATM; Harris, 1998). A number of parameters go into this model
 109 including slope parameter (G), visible to near-IR reflectance ratio ($0.55\ \mu\text{m}$
 110 / $2.5\ \mu\text{m}$), emissivity, and the coupled parameters geometric albedo (p_V), di-
 111 ameter, and absolute magnitude (H). The NEATM assumes that the asteroid
 112 is spherical and that the hottest point on the surface is the sub-solar point
 113 (i.e. the surface is in instantaneous equilibrium with the incident solar flux).
 114 The NEATM thermal beaming parameter η compensates for a lack of ex-
 115 plicit treatment of thermophysical properties like thermal inertia and surface
 116 roughness. In the NEATM, η is inversely proportional to temperature to the
 117 fourth power² and thus can indicate whether the measured thermal emission
 118 is higher or lower than expected from an idealized, smooth surface with zero
 119 thermal inertia at zero phase angle. Previous application of the NEATM to
 120 multi-epoch observations has successfully produced results that are broadly
 121 consistent with those from more sophisticated thermophysical models (e.g.
 122 Mueller et al., 2006; Harris et al., 2007; Delbo et al, 2015).

123 Delbo (2004) presented a comprehensive suite of NEATM models that quanti-
 124 tatively describe thermal variability as a function of solar phase angle as well
 125 as other physical parameters. These models suggest several possible caveats
 126 to the detectability of aspect-dependent thermal variability.

127 (1) The dimensionless thermal parameter Θ (Spencer et al., 1989) quanti-
 128 fies the ratio of radiative to rotational timescales, and is a function of
 129 spin period, thermal inertia (Γ), and subsolar temperature as dictated
 130 by heliocentric distance. Though the smallest near-Earth asteroids can
 131 spin rapidly, the vast majority of NEAs with sizes bigger than about 200

² Technically, in NEATM formalism ηT_{SS}^4 is a constant, where T_{SS} is the sub-solar equilibrium temperature on the surface of the asteroid.

132 meters have rotation periods on the order of several hours (e.g. Polishook
 133 et al., 2012). Thus, for typical NEA rotation periods and heliocentric dis-
 134 tances (~ 1 AU), a thermal inertia greater than about 200 in MKS units
 135 ($\text{J m}^{-2} \text{s}^{-0.5} \text{K}^{-1}$) ensures that heat deposited by solar insolation does
 136 not radiate away so quickly as to prevent morning-afternoon tempera-
 137 ture differences. The typical thermal inertia for asteroids with diameters
 138 $< 5\text{km}$ would be in that range (Delbo et al., 2007). While high thermal
 139 inertia certainly facilitates a morning-afternoon temperature dichotomy,
 140 thermally-constrained poles for several large Main Belt asteroids (Morri-
 141 son, 1977; Hansen, 1977) suggests that either these early determinations
 142 were simply lucky or that high thermal inertia is not an exclusive require-
 143 ment.

- 144 (2) The asteroid must be observable across a wide range of solar phase angles,
 145 particularly at phases in excess of $\sim 50^\circ$. In general, such phase angle
 146 ranges are only accessible for NEAs.
- 147 (3) If thermal emission is to be detected in the near-IR K-band, then the
 148 object needs to be at a heliocentric distance inside of about 1 AU and
 149 have an albedo $< 10\%$.
- 150 (4) The asteroid should be observed during a single apparition to avoid sig-
 151 nificant changes in viewing aspect that could occur across multi-epoch
 152 observations.

153 Even though all of these properties were not necessarily known in advance for
 154 QE2 and FG3, their low albedos and wide range of observable phase angles
 155 made them good candidates for monitoring thermal variability in the near-IR
 156 as a function of viewing aspect.

157 3 Case Study: (285263) 1998 QE2

158 Radar observations of 1998 QE2 in 2013 revealed a diameter of approximately
159 3 km and a prograde rotation state with the pole pointing approximately 40°
160 above the ecliptic³ (Springmann et al., 2014). From the JPL Horizons system
161 the absolute magnitude of QE2 is $H = 17.3$, which is revised from a value
162 of $H = 16.4$ used in previous works (e.g. Trilling et al., 2010). An updated
163 analysis of warm Spitzer observations using this new H magnitude yields a
164 low albedo for QE2 of $3_{-2}^{+3}\%$ (Trilling et al., 2016). We adopt $H = 17.3$, even
165 though it may be less accurate than the value of $H = 16.98$ measured by
166 Hicks et al. (2013), because it is fully consistent with the formal log-normal
167 albedo error bars as computed by Trilling et al. (2016). As we discuss below,
168 these are important for investigating systematic errors in our NEATM models
169 due to uncertainties on the input parameters. Figure 1 depicts a schematic of
170 the opposition-centered orbital geometry of QE2 during its 2013 apparition.
171 To facilitate our analysis we employ a signed phase angle (α) based on the
172 geocentric ecliptic longitude of asteroid opposition, specifically $\alpha < 0^\circ$ when
173 the asteroid’s ecliptic longitude minus the Sun’s ecliptic longitude is greater
174 than 180° . The putative prograde rotation of QE2 suggests that prior to op-
175 position ($\alpha > 0^\circ$) Earth-based observers would preferentially see the cooler
176 morning side of the asteroid, whereas post-opposition ($\alpha < 0^\circ$) observations
177 would preferentially access the warmer afternoon side. Near-IR spectra of QE2
178 spanning opposition are shown in Figure 2.

179 A composite visible/near-infrared spectrum of QE2 is shown at the bottom

³ Incidentally these observations also discovered a small satellite roughly 750 meters in size. Unless the satellite has a dramatically different albedo or thermal properties relative to the primary, its contribution to the system’s measured flux should not significantly influence any of the results presented here.

Fig. 2. IRTF/SpeX spectra of 1998 QE2 taken in the months surrounding its opposition passage in mid 2013. The asteroid spectrum from July 5 also includes visible data ($0.4 - 0.8 \mu\text{m}$) from Hicks et al. (2013). QE2 is taxonomically classified as a Ch-type (DeMeo et al., 2009) and is a close spectral analog to the CM2 carbonaceous chondrite Nogoya. The measured spectra are shown in grey, the NEATM-corrected spectra with thermal tails removed are overplotted in black. Spectra have been vertically offset for clarity.

180 of Figure 2. Due to the presence of a weak $0.7 \mu\text{m}$ absorption feature the
 181 asteroid is best fit by a Ch-type taxonomy in the DeMeo et al. (2009) system.
 182 Using the technique outlined in Moskovitz et al. (2013) we find that QE2 has a

183 spectrum and albedo most closely matched to RELAB (Pieters, 1983) spectra
 184 of carbonaceous chondrites. The CM2 Nagoya is a particularly good spectral
 185 analog (Fig. 2). A potential link between Ch-asteroids and CM chondrites has
 186 been noted previously (e.g. Burbine, 1998). This taxonomic classification is
 187 consistent with the low Spitzer albedo.

188 The spectra in Figure 2 clearly show thermal emission long-wards of $\sim 2\mu\text{m}$.
 189 We model these thermal tails with the following NEATM parameters: geomet-
 190 ric albedo $p_V = 3_{-2}^{+3}\%$ (Trilling et al., 2016); slope parameter $G = 0.086$, equal
 191 to the mean for C-complex asteroids (Warner et al., 2009); visible to near-
 192 IR reflectance ratio = 1.11, measured from our combined visible and near-IR
 193 spectral data (Fig. 2); absolute magnitude $H = 17.3$ from the JPL Horizons
 194 system; and emissivity $\epsilon = 0.9$. These values are either consistent with obser-
 195 vations of QE2 or are typical for objects like QE2, and are held constant for
 196 all of the modeling conducted here. Again we adopt H from JPL as opposed
 197 to Hicks et al. (2013) so that we can propagate the albedo error bars from
 198 Trilling et al. (2016) who also used the JPL value.

199 With each of these parameters held fixed, the beaming parameter η is left as
 200 a free parameter. We vary η to best remove the thermal tails from the spectra
 201 in Figure 2. The best fit η for each spectrum is determined by minimizing the
 202 error-weighted RMS residual between the thermally corrected spectrum and
 203 a linear fit to the data between 1.9 and $2.49\mu\text{m}$. This approach thus requires
 204 three free parameters: η and the two parameters associated with the linear fit.
 205 Uncertainties on the fitted η values reflecting the signal-to-noise of the data
 206 (i.e. statistical errors) are conservatively determined by bracketing the range
 207 of η values that clearly over- or under-compensate the thermal emission. These
 208 uncertainties are somewhat subjective but do correspond to deviations from

the best fit by approximately one-sigma as dictated by the noise level in the spectral data. Best-fit η values and signal-to-noise related uncertainties are given in Table 1 for the nominal assumed albedo of 3%. A similar approach to modeling of near-IR spectra and estimating uncertainties on the model parameters has been employed elsewhere (e.g. Rivkin et al., 2005; Reddy et al., 2012).

We further investigate uncertainty on η by considering systematic errors on the NEATM input parameters which would produce an overall offset to the best-fit η values. The assumed albedo is the dominant source of systematic uncertainty in η , which for QE2 ranges from 1-6% (Trilling et al., 2016). We fit η assuming these extreme values and include those additional fits in Table 1. The uncertain albedo for QE2 results in large systematic errors ($\sim 50\%$) in the absolute η values. However, any change in the albedo from the nominal 3% affects all η values in the same way (increase or decrease) and by approximately the same amount. The assumed value of $G = 0.086$ also represents a potential source of systematic error. However, considering a wide range of G values from -0.1 to +0.15 results in η fits that span less than half the range produced by considering the full extent of possible albedos. In other words the systematic errors induced by uncertain G are approximately 20% on the best fit η values.

The NEATM results for QE2 are shown in Figure 3. An asymmetric trajectory in this $\eta - \alpha$ parameter space can indicate physical properties such as sense of rotation or thermal inertia, however the use of NEATM to diagnose these physical traits must be treated with caution due to known systematic errors inherent to NEATM (Wolters & Green, 2009) and known correlations between η and α (Delbo et al., 2003; Wolters et al., 2008; Masiero et al., 2011). Nevertheless, the results in Figure 3 are suggestive that a small number of carefully

Fig. 3. NEATM η as a function of solar phase angle, α , for 1998 QE2 during its 2013 apparition. As QE2 moved through opposition it tracks from the upper right corner to the lower left of this $\eta - \alpha$ space (black circles). NEATM models for asteroids with prograde rotation, surface roughness $\bar{\theta} = 36^\circ$, and thermal inertia (Γ) of 200 and 400 in MKS units are over-plotted as the solid and dashed grey lines respectively (Delbo, 2004). For a prograde rotator the predicted $\eta - \alpha$ relationship is asymmetric with higher η (lower morning temperatures) at positive phase angles and lower η (higher afternoon temperatures) at negative phase angles. The curves for retrograde rotators would be flipped about $\alpha = 0^\circ$. Statistical errors based on the signal-to-noise of our data are in black, while systematic error bars accounting for uncertainty in albedo are shown in grey.

235 timed observations in the near-infrared, particularly at phase angles $> 50^\circ$,
 236 could be used to constrain physical properties of small NEAs. Unfortunately
 237 the lack of repeat observations of QE2 at high phase angles means that the
 238 results for this specific object are tenuously hinged to the single May 11 data
 239 point.

240 In consideration of this technique, we compare our QE2 results to model curves
 241 extracted from Delbo (2004). Specifically, we compare our η values to a suite

242 of models that correspond to bodies with a macroscopic surface roughness
 243 parameter $\bar{\theta} = 36^\circ$. This particular value was selected as an intermediate
 244 case in the range of models presented by Delbo (2004) and is consistent with
 245 expected roughness parameters from more sophisticated photometric models
 246 of other well studied asteroids (e.g. Delbo & Tanga, 2009). The assumption of
 247 this particular roughness does not significantly influence the results presented
 248 here. If we were to adopt other roughness values (10° , 20° , 58°) then the curves
 249 in Figure 3 would shift by no more than $\sim 10 - 20\%$. More specifically, the
 250 afternoon-side curves ($\alpha < 0^\circ$) remain largely unchanged across all roughness
 251 values, whereas the morning-side ($\alpha > 0^\circ$) curves either get steeper by $\sim 20\%$
 252 for the largest roughness or shallower by $\sim 10\%$ for the smallest roughness
 253 value.

254 As seen in Figure 3, the large η prior to opposition (May 11) suggests a cooler
 255 relative surface temperature, consistent with (though not uniquely diagnos-
 256 tic of) viewing of local morning on the asteroid surface and hence prograde
 257 rotation. Furthermore, the η values and magnitude of the η -enhancement at
 258 high positive phase angles are consistent with models for a prograde rotator
 259 with thermal inertia $\Gamma \sim 200 - 400$ (Delbo, 2004). Interestingly, a thermal
 260 inertia around 200 is the expectation for a ~ 3 -km asteroid like QE2 (Delbo
 261 et al, 2015). Again, the assumption of surface roughness $= 36^\circ$ does not signif-
 262 icantly affect the rough fit to our data by theoretical curves corresponding to
 263 thermal inertia values around 200-400. For the full range of roughness values
 264 considered by Delbo (2004), a thermal inertia of 50 is too low to produce large
 265 variations in η , and thermal inertia of 900 results in values of η that are much
 266 larger than those retrieved from our data. The systematic uncertainty in our
 267 η values due to the range of possible albedos could shift the points in Figure
 268 3 up or down by several tens of percent, however the general result that the

269 data are indicative of a thermal inertia of a few hundred would still hold. Fur-
 270 thermore, the relative orientation and increase at high positive phase angle of
 271 the $\eta - \alpha$ points in Figure 3 would be preserved.

272 4 Case Study: (175706) 1996 FG3

273 The NEA 1996 FG3 is also a binary system (Pravec & Harris, 2000) with a
 274 primary about 1.7 km in size (Wolters et al., 2011; Mueller et al., 2011; Walsh
 275 et al., 2012; Yu et al., 2014), a spacecraft accessible orbit (i.e. $\Delta v = 6.6$ km/s),
 276 and a putative primitive composition (Binzel et al., 2001; de Leon et al., 2011;
 277 Walsh et al., 2012; de Leon et al., 2013). FG3’s satellite is roughly 450 meters
 278 in size (Yu et al., 2014) and is in a tidally-locked retrograde orbit (Benner et
 279 al., 2012; Scheirich et al., 2015), which suggests that the primary is also in
 280 a retrograde spin state. Again, the satellite is unlikely to have a significant
 281 influence on the system’s thermal flux unless it has a dramatically different
 282 albedo or thermal properties relative to the primary. A low albedo around
 283 4% (Wolters et al., 2011) makes FG3 another ideal object for monitoring
 284 thermal variability in the near-IR. As with QE2, the flux contribution from the
 285 small satellite should not have a significant effect on any of the measurements
 286 presented here.

287 Numerous near-IR spectra of FG3 have been obtained during apparitions in
 288 2009 and 2011 (de Leon et al., 2011; Walsh et al., 2012; de Leon et al., 2013).
 289 We analyze four individual spectra from these apparitions (Table 2; Figure 4).
 290 These spectra can be qualitatively divided into two groups: in 2009 the spectra
 291 have a neutral spectral slope and minimal thermal excess, whereas in 2011 the
 292 spectra show a pronounced red spectral slope and clear thermal emission.

Additional near-IR spectra not analyzed here (de Leon et al., 2011; Rivkin et al., 2012) are consistent with this qualitative description. Taxonomically (DeMeo et al., 2009), the 2009 data suggest that FG3 is a member of the C-complex while the 2011 data suggest membership in the X-complex. The repeatability of these spectra on different nights in each of the 2009 and 2011 epochs suggests that this variability is real and not an observational artifact.

We have compared the timing of these observations to predictions for mutual events (P. Scheirich, private communication). Those predictions are included in Table 2. In short, the occurrence of mutual events does not seem to have any major influence on the spectral data, which is not surprising considering the significant size difference between the primary and secondary. The two spectra that differ the most, i.e. the 2009 April 27 and 2011 December 1 data, were both obtained when the secondary was occulted by the primary. Furthermore, within each epoch the pairs of spectra were obtained during different system configurations, again suggesting that the secondary had little optical and thermal influence on the measurements. It is worth noting however that occultation of the primary by the secondary, particular if the secondary shadows the hottest region on the primary’s surface, could have significant thermal implications. This occultation would lead to reduced thermal emission and a correspondingly elevated η . The only data analyzed here that corresponded to occultation of the primary were from 2011 December 30. This data point is further discussed below.

As with 1998 QE2 (§3) we model the thermal tails with the NEATM. The following parameters are employed: geometric albedo $p_V = 3.9 \pm 1.2\%$ (Walsh et al., 2012); absolute magnitude $H = 17.76 \pm 0.03$ and slope parameter $G = -0.07 \pm 0.02$ as measured by Pravec et al. (2006); visible to near-IR reflectance

Fig. 4. Reflectance spectra of 1996 FG3 (grey lines), offset for clarity. In general the data from 2009 display a neutral spectral slope and limited thermal emission, whereas the data from 2011 show a red spectral slope and pronounced thermal emission. Visible data from Binzel et al. (2001) have been appended to the bottom spectrum. NEATM corrected spectra are over-plotted in black.

ratio ranging from 0.9-1.2 as measured from our combined visible and near-IR
spectra; and emissivity $\epsilon = 0.9$. These values are held constant for all of the
FG3 models and again η is left as a free parameter in the NEATM fits. Our
NEATM results for FG3 are shown in Figure 5. As with QE2 we compute error
bars on the derived η values that account for uncertainty due to the signal-to-
noise of the data and we compute systematic offsets in η attributable to the
range of possible albedos for FG3 (Walsh et al., 2012). Again the uncertainty
on albedo is the dominant source of error for these models. Previous results
based on observations at longer wavelengths are also included in Figure 5; in
particular, NEATM η values from $2 - 4 \mu m$ spectral observations by Rivkin
et al. (2013) and thermal infrared ($\sim 8 - 20 \mu m$) photometry by Walsh et al.

Fig. 5. Top panel: The $\eta - \alpha$ relationship for 1996 FG3 based on 2009 (black) and 2011 (grey) observations. Filled circles are the data analyzed here (Figure 4). Statistical errors based on the signal-to-noise of the data are shown in black, systematic errors due to the range of possible albedos are in grey. Open circles are from Rivkin et al. (2013) and the open triangle is from Walsh et al. (2012). NEATM models for a retrograde rotator with thermal inertia (Γ) of 200 and 400 in MKS units, and surface roughness $\bar{\theta} = 36^\circ$ are over-plotted (Delbo, 2004). The curves for prograde rotators would be flipped about $\alpha = 0^\circ$. The 2011 data are broadly consistent with the models for retrograde rotation, however the 2009 data are not. Bottom panel: the geocentric ecliptic latitude of the asteroid at the time of each observation. The discrepancy between the data and the models could be explained by a texturally and spectrally heterogeneous surface revealed by the different viewing geometries, i.e. preferential viewing of the southern hemisphere in 2011 and of the northern hemisphere in 2009.

331 Unlike the $\eta - \alpha$ results for 1998 QE2, the fits in Figure 5 do not clearly follow
 332 the NEATM predictions for a retrograde rotator. In fact the highest values
 333 of η for FG3 correspond to viewing geometries that would have preferentially
 334 viewed the afternoon hemisphere for a retrograde rotator. Our data thus sug-
 335 gest that FG3 is in a prograde rotation state. This apparent contradiction is

discussed in the following section. Values of $\Gamma \sim 200 - 400$ most closely overlap our data points and are broadly consistent, though higher by a factor of ~ 2 , with other estimates for FG3's surface (Wolters et al., 2011). Interestingly the η value for December 30 is slightly higher than expected for a low phase angle observation. As mentioned above this could be attributed to observation of the system while the primary was occulted by the secondary. Modeling of this scenario is beyond the scope of this work, and given the unexplained variability in η for this object we do not pursue this idea any further.

5 Discussion

We have demonstrated the detection of phase dependent variations in thermal beaming parameter for the NEAs (285263) 1998 QE2 and (175706) 1996 FG3. While such variability is not novel – correlations between phase angle and η have been shown previously (e.g Delbo et al., 2003; Wolters et al., 2008; Masiero et al., 2011) – this work represents the first systematic analysis of such variability at near-IR wavelengths. Ultimately the goal of any such investigation would be to correlate actual physical properties with derived model parameters. It is in this vein that we discuss the thermal variability seen for QE2 and FG3.

As discussed above, the NEATM modeling of the QE2 data indicate a significant increase in η at high positive phase angles (Figure 3). This is reasonably well fit with models for a prograde pole orientation and a surface thermal inertia of roughly $200\text{-}400 \text{ J m}^{-2} \text{ s}^{-0.5} \text{ K}^{-1}$, properties which are consistent with other observations (Springmann et al., 2014) and expectations for objects of this size (Delbo et al., 2007). It is unclear whether the pole, pointing

360 at ecliptic latitude $\sim +40^\circ$ is near enough to purely prograde to fully explain
361 the observed thermal effects as a function of solar phase angle.

362 While our QE2 results are suggestive that the thermal variability in the near-
363 IR is indicative of physical properties, a data point at large negative phase
364 angles ($\alpha < -50^\circ$) would have helped to definitively determine whether the
365 apparent asymmetry in this $\eta - \alpha$ space is a signature of pole orientation or
366 simply a side effect of the NEATM method. The diagnostic importance of such
367 high phase angle measurements on both sides of opposition is an important
368 lesson for guiding future observational campaigns. In general, the models of
369 Delbo (2004) suggest that objects with $\Gamma \ll 200$ would not display significant
370 differences in η as a function of phase angle, however future targeting of low
371 albedo NEAs at near-IR wavelengths across a range of sizes are needed to test
372 this model prediction.

373 The interpretation of the FG3 data is less clear, which is perhaps unsurpris-
374 ing given the numerous previous attempts to understand its variability in
375 reflectance and thermal emission (de Leon et al., 2011; Binzel et al., 2012; de
376 Leon et al., 2013). We have built upon these previous works and show that
377 there are clear differences in η as a function of phase angle (Figure 5), and
378 that those differences are asymmetric about opposition. We argue that these
379 differences are not an artifact of any observational issues such as signal-to-
380 noise or data calibration. The 2009 data are of lower signal-to-noise relative
381 to the 2011 data and they do show the greatest offsets from model predictions
382 (Fig. 5), but there are no clear indicators of poor calibration. For example, the
383 near complete removal of any residual telluric absorption features around 2.0
384 μm suggests that the dispersion solution is good and that the atmosphere was
385 stable enough during those nights to enable removal of the telluric bands. Fur-

386 thermore, there are no odd continuum or slope changes in the 2009 data that
 387 might indicate use of a bad solar analog. Certainly, the repeatability of spec-
 388 tral properties in each of the two epochs suggests that the spectral changes are
 389 real. Furthermore, the results of Walsh et al. (2012) and Rivkin et al. (2013)
 390 are in broad agreement with our NEATM η values (Fig. 5), thus providing
 391 further support for a scenario in which spectral and thermal changes did oc-
 392 cur. However, these detected changes, particularly the $\eta - \alpha$ relationship, are
 393 not consistent with an expected retrograde spin state (Scheirich et al., 2015;
 394 Yu et al., 2014). As such, we offer three possible explanations for why our
 395 results may not be consistent with retrograde models, however in all three
 396 cases additional data are needed to better understand the unusual spectral
 397 and thermal behavior displayed by FG3.

398 First, the variability in the data could be a consequence of the known corre-
 399 lation between η and phase angle in NEATM models (Spencer et al., 1989;
 400 Wolters & Green, 2009; Reddy et al., 2012). Values of η derived from NEATM
 401 reflect the observed surface temperature. At high phase angles surface rough-
 402 ness causes increased shadowing and an apparent drop in surface temperature
 403 (i.e. higher η). Such correlations are typically represented as linear fits to an
 404 ensemble of data. Table 3 presents a compilation of coefficients based on linear
 405 fits to various NEA data sets. Also included are fit parameters to the FG3 data
 406 from the 2009 and 2011 apparitions with errors indicating 1σ uncertainties.
 407 These linear fits are error weighted by the systematic uncertainties on each of
 408 the η values. In comparison to the ensemble fits our FG3 values are all shifted
 409 to higher η , i.e. larger intercepts, and shallower slopes. The η values from the
 410 QE2 data are also slightly higher than the mean values from the studies repre-
 411 sented in Table 3. Though it is not entirely correct to compare our two objects
 412 to the diverse ensemble of properties (surface roughness, thermal inertia, mor-

phology, size, spin vector) represented by the population studies in Table 3, it is interesting to consider that these offsets may be due to currently unquantified differences in the η values returned from fitting near-IR data ($< 2.5\mu\text{m}$) versus those obtained by fitting longer wavelength data ($> 2.5\mu\text{m}$). If this is the case then our results provide insight into the magnitude of these offsets – of order several 10’s of percent. However, our limited sample makes it difficult to determine whether this offset is simply a consequence of small number statistics or due to phenomena not treated in the model such as wavelength dependent emissivity.

Table 3
NEATM $\eta - \alpha$ linear-fit coefficients

Reference	Intercept	Slope
Delbo (2004)	0.92 ± 0.07	0.011 ± 0.002
Wolters et al. (2008)	0.91 ± 0.17	0.013 ± 0.004
Mainzer et al. (2011)	0.761 ± 0.009	0.00963 ± 0.00015
This work; FG3 from 2009	1.33 ± 0.12	0.005 ± 0.002
This work; FG3 from 2011	0.94 ± 0.01	-0.0047 ± 0.0005

A second explanation for the mismatch between our data and the retrograde models is the unlikely possibility that FG3 is actually in a prograde state. The analysis of light curve photometry strongly suggests that FG3’s satellite is in a retrograde orbit (Scheirich et al., 2015) and the satellite seems to be tidally locked (Benner et al., 2012). Attempts to model the spin pole of the primary have most recently been inconclusive (Scheirich et al., 2015), but previous analyses suggest a retrograde state (Yu et al., 2014). While a retrograde satellite orbit and a prograde primary spin state seem unlikely from the perspective of binary formation models involving YORP spin-up and mass loss (e.g. Jacobson & Scheeres, 2011), the current ambiguity in the interpretation of the lightcurve data leaves this as an open possibility.

433 Future observations to unambiguously determine the primary spin state would
434 directly test this scenario.

435 Interestingly, the linear fits to our FG3 data are significantly different for
436 each of the two epochs of observation (Table 3). Furthermore, the reflectance
437 spectra of FG3 are distinctly different in each of the two epochs (Figure 4).
438 Perhaps the most interesting comparison to highlight these differences is be-
439 tween the 2009 April 27 and 2011 December 1 data. These data clearly fall into
440 the categories of neutral slope, low thermal emission in 2009, and red slope,
441 high thermal emission in 2011. However the heliocentric distance of FG3 was
442 almost identical on these two dates. The primary difference between these ob-
443 servations is viewing geometry: the solar phase angles are essentially $\pm 50^\circ$ on
444 either side of opposition (Table 2) and the sub-Earth latitudes on the surface
445 of the body were at their maximum separation amongst the data considered
446 here (Fig. 5).

447 This raises a third and ultimately testable interpretation of the FG3 results.
448 As shown in the bottom panel of Figure 5 the two epochs corresponded to
449 two different viewing aspects: in 2009 the asteroid was at negative ecliptic
450 latitude and thus observations preferentially viewed its northern hemisphere,
451 whereas in 2011 the asteroid was at positive ecliptic latitude and thus ob-
452 servations preferentially accessed its southern hemisphere. The variability in
453 optical and thermal properties could thus be suggestive of a heterogeneous
454 surface. The “top-shaped” morphology of FG3 with its pronounced equatorial
455 ridge (Benner et al., 2012; Yu et al., 2014) could serve to isolate the optical
456 and thermal influence of the northern and southern hemispheres and thus ac-
457 centuate surface heterogeneity even though the difference in viewing aspect
458 was only $\sim 20 - 30^\circ$ across the two epochs. If the surface of FG3 is hetero-

459 geneous, then we predict that the northern hemisphere would have optically
 460 neutral reflectance properties and a higher relative albedo, which would lower
 461 surface temperature and yield higher η . Conversely, the southern hemisphere
 462 would have optically red reflectance properties and a lower relative albedo,
 463 which would result in a higher relative surface temperature and correspond-
 464 ingly lower η . FG3 will be a strong optical target in 2022 and will be at negative
 465 ecliptic latitudes, thus providing a vantage of its northern hemisphere. Addi-
 466 tional long term monitoring of this object may ultimately determine whether
 467 its measured variability is due to a heterogeneous surface (de Leon et al., 2011,
 468 2013) or some other physical effect (Binzel et al., 2012). Spectral heterogene-
 469 ity is not commonly seen on asteroids, particularly for km-scale objects like
 470 FG3, however near-IR observations of the 500-meter near-Earth object 101955
 471 Bennu indicate variations in spectral slope that may be related to differences
 472 in regolith grain size across the surface (Binzel et al., 2015).

473 In light of the uncertainty surrounding our FG3 results it remains unclear
 474 whether physical properties like thermal inertia and pole orientation can be
 475 robustly derived from NEATM modeling of thermal emission in K-band. The
 476 highly non-uniform distribution of NEA obliquity, specifically a preference to-
 477 ward purely retrograde states (La Spina et al., 2004), would suggest that this
 478 technique should be well suited to detection of aspect-dependent thermal vari-
 479 ability in the NEA population. Following on the work of Delbo (2004), new
 480 models to quantify the detectability of thermal asymmetry as a function of
 481 obliquity would provide new insight into the feasibility of such observational
 482 studies. Additionally, a larger sample size is needed to definitively determine
 483 whether NEATM modeling at near-IR wavelengths can robustly retrieve phys-
 484 ical properties like pole orientation and thermal inertia.

485 It is clear that any future near-IR-based study of thermal inertia and pole
 486 orientation would require targets that span the widest possible range of phase
 487 angles on either side of opposition. On any given night ⁴, approximately 20% of
 488 observable NEAs ($V < 20$, solar elongation $> 60^\circ$, galactic latitude $> 20^\circ$) are
 489 at phase angles greater than 50° . Some of this uncertainty could be resolved
 490 by extending such phase dependent measurements to longer wavelengths, for
 491 instance photometry at L- and M-bands (3.5 and $4.5 \mu\text{m}$ respectively) or in
 492 the N- and Q-bands (~ 10 and $20 \mu\text{m}$ respectively) which are closer to the
 493 thermal emission peaks typical of NEOs. However, a systematic comparison
 494 of NEATM results based on data in different wavelength regimes is needed
 495 to more completely understand the limitations of this model. Extending mea-
 496 surements to longer wavelengths would have a primary benefit of enabling
 497 detection and modeling of thermal emission for any NEA, not just low albedo
 498 objects like QE2 and FG3. A targeted spectro-photometric survey to monitor
 499 phase-dependent thermal emission from select NEAs could produce an un-
 500 precedented sample of spin vector orientations. Such a sample would provide
 501 direct tests for models of NEA source regions in the Main Belt that depend
 502 on spin orientation and the subsequent direction of semi-major axis drift due
 503 to the Yarkovsky effect (e.g. Bottke et al., 2002).

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⁴ Based on a filtering of NEAs with the observability tool at <http://asteroid.lowell.edu/upobjjs>.

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