PHYSICAL CHARACTERIZATION AND ORIGIN OF BINARY NEAR-EARTH ASTEROID (175706) 1996 FG3

Kevin J. Walsh1, Marco Delbo’2, Michael Mueller2,3, Richard P. Binzel4, and Francesca E. DeMeo4

1 Southwest Research Institute, 1050 Walnut Street Suite 400, Boulder, CO 80302, USA; kwalsh@boulder.swri.edu
2 UNS-CNRS-Observatoire de la Côte d’Azur, BP 4229, 06304 Nice Cedex 04, France
3 Low Energy Astrophysics, SRON, Postbox 800, 9700AV Groningen, The Netherlands
4 Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 2011 June 30; accepted 2012 January 19; published 2012 March 13

ABSTRACT
The near-Earth asteroid (NEA) (175706) 1996 FG3 is a particularly interesting spacecraft target: a binary asteroid with a low-Δv heliocentric orbit. The orbit of its satellite has provided valuable information about its mass density while its albedo and colors suggest it is primitive or part of the C-complex taxonomic grouping. We extend the physical characterization of this object with new observations of its emission at mid-infrared wavelengths and with near-infrared reflection spectroscopy. We derive an area-equivalent system diameter of 1.71±0.07 km and a geometric albedo of 0.04±0.04, consistent with a taxonomic classification in the C complex. It should be noted that their diameter and albedo values are based on an assumed color temperature (as opposed to a measured one), subjecting their results to significant systematic uncertainty. Wolters et al. (2011), observing at the Very Large Telescope (VLT), determined an effective diameter of 1.71±0.07 km and a geometric albedo of pv = 0.044±0.004; furthermore, they estimate the thermal inertia to be Γ = 120±50 J m−2 s−0.5 K−1. Mueller et al. (2011) also studied the thermal history of 1996 FG3 over its chaotic orbital evolution finding that it was likely (90%) heated above 482 K, possibly hot enough to induce thermal alteration of previously primitive surface material.

Pravec et al. (2000) and Mottola & Lahulla (2000) estimated that 1996 FG3 is a C-type body from its broadband color indices and the steep phase dependence. The second phase of the SMASH survey’s visible wavelength spectroscopy (0.44–0.92 μm) classified 1996 FG3 as a C-type (Bus 1999), and when the spectroscopy of 1996 FG3 was extended to 0.4–1.6 μm by Binzel et al. (2001) 1996 FG3 remained classified as a C-type. Recently, the taxonomic classification scheme of DeMeo et al.

Key word: minor planets, asteroids: general

1. INTRODUCTION

Among the ~37 known near-Earth asteroids (NEAs) with satellites, (175706) 1996 FG3 has a particularly low Δv value, making it an ideal target for a spacecraft mission (Perozzi et al. 2001; Christou 2003; Johnston et al. 2010). In fact, it is the baseline target of the ESA mission study Marco Polo-R (Barucci et al. 2011). (175706) 1996 FG3, hereafter 1996 FG3, is a prototype for the “asynchronous” NEA binaries. About 15% of all NEAs and small Main Belt asteroids (D < 10 km) are estimated to be such a binary (Pravec et al. 2006), and are characterized by a rapidly rotating primary (P < 4 hr), a nearly spherical or oblate primary, and a moderately sized secondary on a close orbit (Pravec et al. 2006).

1996 FG3 was the first binary NEA for which eclipse events were detected in optical wavelengths (Pravec et al. 2000; Mottola & Lahulla 2000). From these and later observations, Scheirich & Pravec (2009) found the period of the mutual orbit to be 16.14±0.01 hr, and a diameter ratio of D2/D1 = 0.28±0.01. A circular orbit is consistent with the data, but the preferred solution has e = 0.10±0.15 and semimajor axis a ∼ 3.4 primary radii. The primary is an oblate ellipsoid with an axis ratio around a/b ∼ 1.2, while the secondary is prolate with an axis ratio around 1.4. The spin period of the primary is 3.6 hr; that of the secondary is unknown. Scheirich & Pravec (2009) also find a mass density of 1.4+0.5−0.6 g cm−3 and an ecliptic latitude of the mutual spin axis of −84°.

The formation of these binaries points to a history of spin rate increase due to the thermal YORP effect, followed by reshaping and mass-loss ending with a satellite in a close orbit (Walsh et al. 2008; see also Scheeres’ 2007 work on fission of contact binary asteroids). This process demands a “rubble pile” or gravitational aggregate makeup, where bulk reshaping is the cause for the ubiquitous oblate “top-shape” and equatorial ridge (see 1999 KW4; Ostro et al. 2006). The process may end with preferential material migration from the poles of the primary toward the equator and also with general regolith depletion (Walsh et al. 2008; Delbo’ et al. 2011).

Photometric observations determined the optical magnitude H = 17.76±0.03 and phase coefficient G = −0.07±0.02 (Pravec et al. 2006). Based on thermal observations (3.6 and 4.5 μm) using the “Warm Spitzer” space telescope, Mueller et al. (2011) find an area-equivalent diameter of this binary system of 1.8±0.6 km and a geometric albedo of pv = 0.04+0.04−0.03, consistent with a taxonomic classification in the C complex. It should be noted that their diameter and albedo values are based on an assumed color temperature (as opposed to a measured one), subjecting their results to significant systematic uncertainty. Wolters et al. (2011), observing at the Very Large Telescope (VLT), determined an effective diameter of 1.71±0.07 km and a geometric albedo of pv = 0.044±0.004; furthermore, they estimate the thermal inertia to be Γ = 120±50 J m−2 s−0.5 K−1. Mueller et al. (2011) also studied the thermal history of 1996 FG3 over its chaotic orbital evolution finding that it was likely (90%) heated above 482 K, possibly hot enough to induce thermal alteration of previously primitive surface material.

Pravec et al. (2000) and Mottola & Lahulla (2000) estimated that 1996 FG3 is a C-type body from its broadband color indices and the steep phase dependence. The second phase of the SMASH survey’s visible wavelength spectroscopy (0.44–0.92 μm) classified 1996 FG3 as a C-type (Bus 1999), and when the spectroscopy of 1996 FG3 was extended to 0.4–1.6 μm by Binzel et al. (2001) 1996 FG3 remained classified as a C-type. Recently, the taxonomic classification scheme of DeMeo et al.

* Partially based on observations obtained at the European Southern Observatory (ESO, program ID 383.C-0179A). Observations were also obtained at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement No. NCC 5-538 with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program.
(2009) has leveraged data reaching 2.45 μm, though DeMeo et al. did not initially examine 1996 FG3. De León et al. (2011) recently analyzed three spectra of 1996 FG3, finding multiple acceptable taxonomic classifications; Ch-, C-, Xk-, and B-type.

In this study, we present new multi-wavelength observations, reflectance spectroscopy between 0.4 and 2.5 μm, and thermal-infrared photometry from 8–19 μm to extend the physical characterization of 1996 FG3. We utilize dynamical modeling of Main Belt source regions for NEAs and analyze the possibility of the B-type Polana family as a source for 1996 FG3.

2. THERMAL-IR OBSERVATIONS AND THERMAL MODELING

We measured the thermal emission of 1996 FG3 from observations at mid-IR wavelengths (8–18.5 μm) and also obtained its visible reflected light. Combined with a suitable model of the surface thermal emission we determined its size and albedo; results are given in Section 2.3.

2.1. IRTF-MIRSI Observations

We observed 1996 FG3 on 2009 May 1 UT using the Mid-Infrared Spectrometer and Imager (MIRSI; Deutsch et al. 2003; Kassis et al. 2008) on the NASA Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii. We used photometric filters centered at 8.7, 9.8, 11.6, and 18.4 μm with spectral bandwidths just short of ∼10%. A standard four-point chop-nod pattern was used to remove background flux. The night was clear with no perceptible clouds, and the atmospheric humidity decreased from ∼30% to ∼6%. The Cohen et al. (1995) flux calibrator α Hya was observed before and after the target at very similar airmass. A second Cohen et al. (1995) standard, α Boo, was observed afterward for cross-checks on the flux calibration. The IRTF IDL library\(^5\) was used to co-add data as needed and to remove known instrument artifacts. Raw signal counts were derived using standard synthetic aperture procedures. Flux calibration factors and atmospheric extinction coefficients for each filter were derived from the observations of α Hya. Analyzing the calibrator observations (including α Boo), we reproduce their Cohen et al. (1995) fluxes to within 1% for N-band filters and to within 4% for Q band (18.4 μm). Color corrections to asteroid fluxes are expected to be at the percent level and were not applied. Final MIRSI fluxes are given in Table 1.

In the N-band filters, we typically performed one or two back-to-back repeat observations to ascertain repeatability, which was within 10%. No such variation is seen in repeat observations of the flux calibrators, likely due to fluctuations in the background level. Our observations cover a fraction of the 3.6 hr rotation period (with a low-amplitude light curve), and given the reported repeatability, no light-curve correction was attempted.

MIRSI observations were interspersed with V-band photometry observations using the optical CCD Apogee, which was calibrated against observations of Landolt (1973) standard SA 101-57. Due to the proximity in airmass ( < 0.05), extinction correction is not critical; we assumed an extinction coefficient of 0.12 mag airmass\(^-1\). The 12 measured V magnitudes are constant within the photometric uncertainty of typically 0.15 mag per data point; no indication of a V-band light curve was detected. The average V mag measured is 16.94, in excellent agreement with the expected V magnitude of 16.94 ± 0.13

\(^5\) http://irtfweb.ifa.hawaii.edu/~elv/mirsi_steps.txt

### Table 1

| UT       | Wavelength (μm) | Flux (Jy) | Flux \((10^{-14} \text{ W m}^{-2} \text{ μm}^{-1})\) |
|----------|-----------------|-----------|---------------------------------|
| 05:51    | 11.6            | 1.23 ± 0.03 | 2.75 ± 0.07                     |
| 05:53    | 11.6            | 1.29 ± 0.03 | 2.87 ± 0.07                     |
| 05:54    | 11.6            | 1.35 ± 0.03 | 3.01 ± 0.07                     |
| 05:59    | 8.7             | 0.86 ± 0.02 | 3.40 ± 0.08                     |
| 06:01    | 8.7             | 0.77 ± 0.02 | 3.06 ± 0.08                     |
| 06:10    | 18.4            | 1.80 ± 0.16 | 1.59 ± 0.14                     |
| 06:17    | 9.8             | 0.96 ± 0.04 | 3.00 ± 0.13                     |
| 06:20    | 9.8             | 1.05 ± 0.05 | 3.27 ± 0.15                     |
| 06:23    | 9.8             | 0.96 ± 0.04 | 3.01 ± 0.14                     |
| 06:25    | 11.6            | 1.23 ± 0.03 | 2.75 ± 0.06                     |
| 06:27    | 11.6            | 1.21 ± 0.03 | 2.69 ± 0.07                     |
| 06:30    | 8.7             | 0.75 ± 0.02 | 2.98 ± 0.08                     |
| 06:33    | 8.7             | 0.69 ± 0.02 | 2.74 ± 0.09                     |
| 06:36    | 8.7             | 0.76 ± 0.02 | 3.02 ± 0.08                     |
| 06:43    | 18.4            | 1.80 ± 0.16 | 1.59 ± 0.14                     |
| 06:48    | 11.6            | 1.10 ± 0.03 | 2.44 ± 0.07                     |
| 06:51    | 9.8             | 0.90 ± 0.05 | 2.80 ± 0.15                     |

Notes. 1996 FG3 was at a heliocentric distance of \(r = 1.057\) AU, observer-centric distance of \(Δ = 0.1567\) AU, and phase angle of \(α = 67°.4\) all values were constant during our observations to within the last quoted digit.

for the light-curve average (based upon \(H = 17.76 ± 0.03, G = −0.07 ± 0.02\); Pravec et al. 2006).

2.2. VLT-VISIR Observations

Independent thermal-IR observations of 1996 FG3 were obtained on 2009 May 2 UT using the VLT Imager and Spectrometer for mid-Infrared (VISIR; Lagage et al. 2004) installed at the 8.2 m VLT Melipal telescope of the European Southern Observatory (ESO), Cerro Paranal, Chile. Photometric observations were carried out through narrowband filters centered at 8.59, 11.88, and 18.72 μm. The observation design was largely analogous to that of our MIRSI observations (see Section 2.1). The Cohen et al. (1995, 1999) standard star HD 93813 was observed at an airmass very similar to that of the science target and used for absolute flux calibration.\(^6\) Data were reduced as described above, except in the case of the PAH_2 filter centered at 11.88 μm, where co-added asteroid data appeared “smoozed.” In order to correct for the flux lost outside the nominal 10 pixel radius synthetic aperture, the nominal 11.88 μm flux was increased by a factor of 13%, derived using the growth curve method (Howell 1989). To test the importance of this approximation we fit the data both without this point and also with this point with a 10% and 20% uncertainty, finding at most a 3% change in diameter and no change in \(η\). See Table 2 for final fluxes.

2.3. Diameter and Albedo Results

We used the Near-Earth Asteroid Thermal Model (NEATM; Harris 1998)\(^7\) to fit the thermal fluxes reported in Tables 1 and 2. NEATM fluxes are calculated by integrating the Planck function over the visible and illuminated part of the surface of a spherical model asteroid. The surface is assumed to be in instantaneous thermal equilibrium with the absorbed sunlight, where temperatures across the surface can be rescaled to

\(^6\) See http://www.eso.org/sci/facilities/paranal/instruments/visir/tools/zerop_cohen_Jy.txt

\(^7\) See also Delbo’ & Harris (2002) for an introduction and overview.
match the spectral energy distribution of the observed fluxes. This temperature rescaling is expressed in terms of a dimensionless “beaming parameter” η such that $T^4 \propto \eta$. Note that our observations do not spatially resolve 1996 FG3. Thus, the NEATM-derived diameter $D$ is that of a sphere with the combined cross-sectional area of the two components. The (area-equivalent) component diameters $D_1$ and $D_2$ are related to $D$ via $D_1^2 + D_2^2 = D^2$. In order to determine the statistical uncertainty in the fit parameters of the NEATM, $D$, $p_V$, and η, we performed a Monte Carlo analysis analogous to that described by Mueller et al. (2007) in which 300 random flux sets are generated, normally distributed about the measured data. The median of the Monte Carlo results is adopted as the nominal result with asymmetric error bars encompassing the central 68.2% of the results (see Mueller et al. 2011 for a more detailed discussion of this method).

This Monte Carlo analysis was performed for each data set (see Tables 1 and 2) and for their combination—note that the observation geometry is essentially identical between the two nights; the corresponding change in expected flux is of the order of 1.6%. Given the apparent discrepancy between the $Q$-band fluxes measured during the two nights (see below), we repeat this analysis for all data sets minus $Q$-band fluxes. All results along with Monte Carlo uncertainties are given in Table 3. The data are plotted in Figure 1 along with the adopted best-fit model curve.

The true uncertainties in $D$ and $p_V$ are dominated by the systematic uncertainty inherent in the NEATM, which is conventionally estimated to be 15% in $D$ and 30% in $p_V$ (Harris 2006). In the (exceptional) case of 1996 FG3, the uncertainty in $H$ does not contribute significantly to the error budget. Our results from the different data sets are in excellent mutual agreement; in particular, the $Q$-band fluxes are largely inconsequential for our purposes. We adopt the average of the first six lines in Table 3 as our final result, including the systematic $D$ and $p_V$ uncertainty; the adopted η uncertainty is the scatter between the six data sets: $D = 1.90 \pm 0.28$ km, $p_V = 0.039 \pm 0.012$, and $\eta = 1.61 \pm 0.08$. Using the known diameter ratio of $D_2/D_1 = 0.28^{+0.01}_{-0.02}$ (Scheirich & Pravec 2009), the corresponding (area-equivalent) component diameters are $D_1 = 1.83 \pm 0.28$ km and $D_2 = 0.51 \pm 0.08$ km.

Our results are in excellent agreement with those reported by Mueller et al. (2011) based on Warm-Spitzer observations ($D = 1.8^{+0.06}_{-0.05}$ km and $p_V = 0.04^{+0.04}_{-0.03}$) and with those reported by Wolters et al. (2011; $D = 1.71 \pm 0.07$ km, $p_V = 0.044 \pm 0.004$, and $\eta = 1.15$). Note that Wolters et al.’s observations took place at a significantly lower phase angle (11\degree 7) than ours (67\degree 4), hence the difference in best-fit η values is consistent with expectations (Delbo’ et al. 2007). Mueller et al. (2011) did

Table 2
VISIR Observations of 1996 FG3 on 2009 May 2 UT

| UT   | Wavelength (μm) | Flux (Jy) | Flux (10^{-14} W m^{-2} μm^{-1}) |
|------|----------------|-----------|----------------------------------|
| 00:56 | 8.59           | 0.68 ± 0.01 | 2.95 ± 0.05 |
| 01:14 | 8.59           | 0.73 ± 0.01 | 2.77 ± 0.05 |
| 00:28 | 11.88          | 1.19 ± 0.02 | 2.53 ± 0.05 |
| 01:05 | 18.72          | 1.31 ± 0.07 | 1.12 ± 0.06 |

Notes. The target was at an observer-centric distance of 0.156 AU, a heliocentric distance of 1.053 AU, and a phase angle of 69\degree 1. Note that the 11.88 μm flux quoted here includes the 13% smearing correction discussed in the text.

Table 3
NEATM Fit Results for 1996 FG3

| Data Set | $D$ (km) | $p_V$ | η          |
|----------|----------|-------|------------|
| MIRSI+Q  | 1.95^{+0.06}_{-0.07} | 0.036^{+0.003}_{-0.002} | 1.67^{+0.08}_{-0.13} |
| MIRSI−Q  | 1.90^{+0.07}_{-0.06} | 0.039^{+0.003}_{-0.002} | 1.59^{+0.10}_{-0.10} |
| VISIR+Q  | 1.81^{+0.07}_{-0.07} | 0.043^{+0.004}_{-0.003} | 1.51^{+0.10}_{-0.09} |
| VISIR−Q  | 1.84^{+0.11}_{-0.06} | 0.041^{+0.005}_{-0.003} | 1.55^{+0.14}_{-0.06} |
| Both+Q   | 1.94^{+0.03}_{-0.06} | 0.037^{+0.005}_{-0.003} | 1.67^{+0.03}_{-0.08} |
| Both−Q   | 1.96^{+0.05}_{-0.06} | 0.036^{+0.005}_{-0.002} | 1.69^{+0.06}_{-0.09} |
| Adopted  | 1.90 ± 0.28 | 0.039 ± 0.012 | 1.61 ± 0.08 |

Notes. Each data set is analyzed with and without $Q$-band data. Adopted final results are given in the last line. The uncertainties in the first six lines are purely statistical, whereas the last line includes systematics.
Figure 2. Visible–near-IR spectral reflectance from 0.4–2.5 μm for 1996 FG3, 1996 FG3 with the thermal tail removed, (142) Polana, and 1999 RQ36 (Clark et al. 2011).

not constrain η, but assumed a value. The good mutual diameter agreement of these three studies therefore provides independent support for the assumptions made by Mueller et al. (2011).

3. VISIBLE–NEAR-IR REFLECTANCE AND 1996 FG3’s MAIN BELT ORIGIN

As part of the MIT-UH-IRTF Joint Campaign for NEO Spectral Reconnaissance, the reflectance of 1996 FG3 was measured between 0.8 and 2.5 μm (where NEO is near-Earth object). In Figure 2, the visible reflectance from the SMASS survey is combined with the near-IR to provide reflectance from 0.37 to 2.5 μm (Binzel et al. 2004). The spectrum presented was measured on 2009 March 30. A total integration time of 2880 s was obtained during a one-hour interval beginning at 11:17 UT. A nearby solar analog star, Landolt 105-76, was observed at similar airmass immediately following the asteroid measurements.

The 2009 March 30 spectrum of 1996 FG3 does not yield a unique class; rather, the allowable classes of C-, Ch-, or Xk-type was determined by the online visible–near-IR taxonomy classifier based on the DeMeo visible–near-IR taxonomy (DeMeo et al. 2009; De León et al. 2011). However, a B-type classification in the DeMeo taxonomy demands a negative slope to 2.45 μm, and in the spectrum a thermal tail is evident starting at ~2.0 μm (see Figure 2). We fit the NEATM to the thermal tail of the SpeX data using the method described in Delbo’ et al. (2011). A large range in pv–η combinations fit the thermal tail well, though we use pv = 0.04, η ≈ 1.2. The phase angle during the SpeX observations was ~8°, i.e., much lower than during our mid-IR photometric observations, hence such a low η is consistent with our expectations.

The thermally corrected spectrum was classified as a B-type by the online classification system (DeMeo et al. 2009). De León et al. (2011) find that the 2009 April 27 spectrum also taken by the MIT-UH-IRTF campaign of lower signal to noise (S/N) is classified as a B-type by the same online tool. However, their spectrum, taken at the Telescopio Nazionale Galileo (TNG) on 2011 January 9, is labeled a Ch- or Xk-type. We move forward with a B-type classification, though naming a taxonomic type is less indicative of composition than an analysis of spectral features. Therefore, we provide a quantitative comparison and a qualitative interpretation of inferred spectral features.

The ≈50 km Main Belt asteroid (142) Polana is the largest member of a family proposed to have been the Main Belt origin of B-type NEO 1999 RQ36 (Campins et al. 2010b), due in large part to its B-type spectrum. To quantify the similarity between these spectra we follow the χ² formulation used by De León et al. (2010) and Campins et al. (2010b) between 0.475 and 1.925 μm with a spacing of 0.0025 μm. Campins et al. (2010b) found a χ² = 4.91 when comparing 1999 RQ36 with (142) Polana. Using a similar, but not exact, wavelength range we find a value χ² = 4.83 for these two objects. 1996 FG3 compared to 1999 RQ36 and (142) Polana yield values of χ² = 1.09 and 1.86, showing strong similarity to both. The closest fit found by Campins et al. (2010b) for 1999 RQ36 and 27 Main Belt B-type asteroids was χ² = 1.33, so its likeness to another B-type such as 1996 FG3 is naturally greater than that to the other Main Belt bodies in that study. Similarly, the match between 1996 FG3 and (142) Polana is also closer than for 1999 RQ36 and (142) Polana. However, when comparing spectra via a χ² routine, features representing mineralogical differences can be marginalized in favor of bulk shape or slope.

There are subtle but clearly revealed differences between the three asteroids (Figure 2) that may allow differing mineralogical interpretations. The features near 1.2 and 2.0 μm for 1996 FG3 are consistent with the presence of some olivine and some pyroxene, where the shallow depth of the features could be due to opaques. Note, however, that De León et al. (2011) reject these two features due to the shape and location of the first band. This is an important disagreement, as our interpretation imply silicates, whereas De León et al. (2011) do not. The deeper 1.2 μm feature for Polana, with no feature at 2.0 μm, is consistent with the presence of olivine (and perhaps opaques). Having spectral hints of olivine and pyroxene is possibly consistent with the spectral properties of ureilite meteorites (Cloutis et al. 2010), whereas the interpretation of De León et al. (2011) is more suggestive of carbonaceous chondrites (they suggest CM2). However, 1999 RQ36 is itself distinct from the others for its lack of 1 and 2 μm spectral features, which is more typical of carbonaceous chondrites.

De León et al. (2011) also made comparisons with meteorite spectra from the RELAB database. Their TNG spectra was best fit by a combination of CM2 carbonaceous chondrites, and L4 and H5 ordinary chondrites. Their preferred match for the high-S/N MIT data was with a weakly shocked H4 ordinary chondrite.

4. DYNAMICAL HISTORY AND 1996 FG3’S MAIN BELT ORIGIN

The chaotic nature of NEA orbital evolution makes it impossible to know the exact history for any given body. However, detailed orbital evolution modeling by Bottke et al. (2002) allows probabilistic estimates for Main Belt source regions to be made. The Bottke et al. (2002) work finds that the current orbit of 1996 FG3 supports a 92% likelihood that it became an NEA after escaping the inner Main Belt via the ν6 secular resonance.8

The ν6 marks the inner limit of the main asteroid belt and thus asteroids only reach this resonance by migrating inward from orbits with a larger semimajor axis (a > 2.15 AU). Similarly,

8 This probability was determined using the three-source NEO model, where three Main Belt sources are modeled as the parent populations for NEOs. This is the technique used for 1999 RQ36 by Campins et al. (2010b).
this region is bounded at large semimajor axis by the 3:1 mean motion resonance (MMR) with Jupiter located at 2.5 AU. Thus, escape by the $v_6$ resonance requires an initial semimajor axis range of $2.15 \text{ AU} < a < 2.5 \text{ AU}$, and inward migration. Escape by the $v_6$ largely retains the inclination of the orbit so that the current $i = 1.99$ inclination is likely near its original inclination in the Main Belt.

A similar analysis has been done for the NEA 1999 RQ36 where its orbital, physical, and rotation properties were used to infer a parent family in the inner Main Belt. Its match with the (142) Polana family is due in large part to its classification as a B-type asteroid, and similarities in their visible/near-IR spectra. Dynamically, 1999 RQ36 was found to have a 95% probability of coming from the inner belt via the $v_6$ resonance, and has a low inclination of $i = 6.04$. 1999 RQ36 is in retrograde rotation, and also has a “top shape” which has been found frequently among binary NEAs (Nolan et al. 2007; Harris et al. 2009).

Despite uncertainties in the Polana family’s age, small members ($H > 18.5$) have already reached the $v_6$ resonance by the Yarkovsky effect (Campins et al. 2010b). The retrograde rotation of 1999 RQ36 also indicates that its Yarkovsky drift is inward, allowing it to drift from the (142) Polana family toward the $v_6$ resonance.

1996 FG3, however, has $H = 17.76$ and thus should not have had time to reach the $v_6$ resonance by the Yarkovsky effect according to this estimate of the Polana family extent (Campins et al. 2010b). (Note also that no definitive age is known for Polana due to its member’s overlap with the Nysa family.) However, it is possible for objects the size of 1996 FG3 to reach the overlapping Jupiter 7:2 and the Mars 5:9 resonances located at $a = 2.2559 - 2.2569$ AU and $a = 2.2542 - 2.2550$ AU (Morbidelli & Nesvorny 1999; Bottke et al. 2007).

This region of overlapping resonances is discussed in the supplementary material of Bottke et al. (2007), but its efficiency as a source is uncertain for objects of 2 km such as 1996 FG3. Figure S6 of Bottke et al. (2007) shows roughly equal numbers of 5 km bodies jumping the resonance or getting trapped and excited.

Smaller objects will have higher Yarkovsky drift rates, likely lowering the fraction that get excited onto planet-crossing orbits. We tested the efficiency of resonance-crossing for ~2 km bodies drifting at their maximum Yarkovsky drift rates, which provides a lower limit. We used a modified version of swift_rmsv that applied a constant change in semimajor axis of $\Delta a = 10^{-4}$ AU Myr$^{-1}$ as estimated from Bottke et al. (2006) as an upper limit for its Yarkovsky drift rate at this size. We tested a set of 155 massless test particles initially located at $a \approx 2.26$ AU. The particles had initial $e$ and $i$ values similar to those of Polana, and 21 of the 155 particles had their eccentricities excited to Mars-crossing levels while crossing the resonance, and evolving onto Mars-crossing orbits (see Figure 3). From here their evolution onto NEO orbits will be relatively rapid and leave them virtually indistinguishable from asteroids entering NEO space via the $v_6$ resonance.

The 21 particles excited out of the inner Main Belt all had initial eccentricities above 0.15, pointing to the resonance’s increasing effectiveness for higher $e$. The Polana family itself covers a range from $e = 0.13$ to 0.17, even though (142) Polana itself has an $e = 0.136$. Even with the conservative assumption of the maximum Yarkovsky drift rate for a $D = 2$ km asteroid, approximately 10% of the $i$ of family members this size would exit the inner Main Belt by the overlapping J7.2 and M5:9 resonances. Therefore, 1996 FG3 could still have an origin with the Polana family as it fits the other major criteria used by Campins et al. (2010b) to locate (142) Polana as a possible parent family of 1999 RQ36: a B-type asteroid, a likely inner Main Belt origin, low inclination, retrograde rotation. Making this study more general, to estimate the number of Polana members of this size in the NEO population, is challenging due to the uncertainties surrounding the exact size and age of the Polana family.

5. RESULTS AND CONCLUSIONS

The findings of these observations and dynamical studies are as follows.

1. 1996 FG3 has a diameter of $1.90 \pm 0.28$ km and a geometric albedo of $p_V = 0.039 \pm 0.012$.

2. Available data do not uniquely place 1996 FG3 into a single taxonomic class; the best data (highest S/N) with a thermal flux correction applied are most consistent with the B-class.

3. 1996 FG3 is likely (92%) to have come from the inner Main Belt via the $v_6$ resonance, though it could have escaped by the overlapping J7.2/M5:9 resonances located at 2.255 AU.

Together, these results provide a much better picture of the origin of 1996 FG3 and raise some tantalizing questions about its relation to the NEA 1999 RQ36, another ideal space-mission target and primary target of NASA’s OSIRIS-REx sample return mission (Lauretta et al. 2010).

Delbo’ et al. (2011) studied the thermal properties of binary NEAs that have been observed in the thermal-IR, finding that statistically elevated $\eta$ values, used as a proxy for thermal inertia, pointed to cooler surfaces than non-binary NEAs. This was interpreted in terms of regolith loss during the binary formation process. Here, 1996 FG3 was fit with an $\eta$ of...
1.61 ± 0.08. The large phase angle of ~68° makes this less constraining, but the values are elevated compared to the sample presented in Delbo’ et al. (2011). Wolters et al. (2011) obtained $\eta \sim 1.15$ at a phase angle of 11°.7. Taken together, the available thermal-IR data should enable a robust determination of the thermal inertia; that is, however, beyond the scope of this paper. 1999 RQ$_{36}$, in comparison, has a thermal inertia of ~600 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ (Emery et al. 2010), higher than the NEA average of ~200 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ (Delbo’ et al. 2007). However, a value of the thermal inertia higher than 200 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ is expected for 1999 RQ$_{36}$ since there is an inverse correlation between thermal inertia and asteroid size (Delbo’ et al. 2007) and because 1999 RQ$_{36}$ has a diameter of 580 m (Nolan et al. 2007) while the average thermal inertia value of 200 J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ is appropriate for NEAs of about 2 km in diameter. The radar shape of 1999 RQ$_{36}$, oblate with a possible equatorial ridge, was suggestive of post-YORP-spinup and reshaping, and the Emery et al. (2010) thermal inertia measurement supports this.

1996 FG$_{3}$ and 1999 RQ$_{36}$ share many physical properties and possibly a similar dynamical history. As shown in Section 3, there is some uncertainty about the precise taxonomy for 1996 FG$_{3}$, though its spectra is qualitatively similar, with a negative slope from 0.5 to 2.0 μm, to that of 1999 RQ$_{36}$. The features for 1996 FG$_{3}$ at 1.2 and 2.0 μm are an important distinction between 1996 FG$_{3}$ and 1999 RQ$_{36}$. If these features are indicative of silicates, then 1996 FG$_{3}$ may have more similarities with 1996 FG$_{3}$ and 1999 RQ$_{36}$ share many physical properties and possibly a similar dynamical history. As shown in Section 3, there is some uncertainty about the precise taxonomy for 1996 FG$_{3}$, though its spectra is qualitatively similar, with a negative slope from 0.5 to 2.0 μm, to that of 1999 RQ$_{36}$. The features for 1996 FG$_{3}$ at 1.2 and 2.0 μm are an important distinction between 1996 FG$_{3}$ and 1999 RQ$_{36}$. If these features are indicative of silicates, then 1996 FG$_{3}$ may have more similarities with

It is important to note that Jenniskens et al. (2009) obtained a low S/N visible spectrum of asteroid 2008 TC$_{3}$ prior to its Earth impact and subsequent recovery as the Almahata Sitta meteorite. While their initial interpretation of this spectrum suggested F- or B-type classification in the system of Tholen (1989), that classification is not confirmed with the addition of near-infrared spectra of an Almahata Sitta meteorite presented by Jenniskens et al. (2010) and Hiroi et al. (2010). While a composite average spectrum of different stones of Almahata Sitta reproduces the 2008 TC$_{3}$ visible spectrum, none of the measured lab spectra matches the B-class (or any asteroid class defined over the full spectral range defined by DeMeo et al. 2009).

We also note that the F-class itself diverges (fails to exist) for objects whose spectra are extended from the visible wavelengths to the near-infrared. As discussed by DeMeo et al. (2009), objects that are spectrally similar over visible wavelengths and satisfy the Tholen (1989) definition of the “F-class” diverge from one another as their spectra are extended into the near-infrared. Thus, at present, the visible plus near-infrared spectrum of the Almahata Sitta meteorite spectrum fits into no asteroid taxonomy class and closely resembles no other currently measured spectrum of any asteroid.

Jenniskens et al. (2010) also pursued a parent source family for 2008 TC$_{3}$ similar to the dynamical work of Campins et al. (2010b) for 1999 RQ$_{36}$. The most probable source region was found to be the inner main asteroid belt via the v$_{6}$ resonance (~80% probability), the same source region as 1996 FG$_{3}$ and 1999 RQ$_{36}$. Jenniskens et al. (2010) speculated the (142) Polana family as a source for 2008 TC$_{3}$. However, the jumbled asteroid–meteorite link for the spectrum of 2008 TC$_{3}$ renders any further connection beyond the scope of this work.

The implication of this study are that two prime space-mission targets, 1999 RQ$_{36}$ and 1996 FG$_{3}$, share similar taxonomies, spectra, and possibly even rotation history (YORP-spinup). Linking them to the same parent family in the inner Main Belt, the Polana family, is highly speculative as 1996 FG$_{3}$ would have had to escape by a minor resonance rather than v$_{6}$. However, it cannot be ruled out entirely as we have shown that the J7:2/M5:9 resonances can push asteroids these size onto Mars-crossing orbits and on the path to near-Earth orbits.

Thanks to Tom Burbine for a helpful discussion, and David Nesvorný for his version of swift_TEA_v3. M.M. and R.P.B. are Visiting Astronomers at the Infrared Telescope Facility, which is operated by the University of Hawaii under Cooperative Agreement no. NNX-08AE38A with the National Aeronautics and Space Administration, Science Mission Directorate, Planetary Astronomy Program. The great work of the IRTF team, and particularly of the TOs, is gratefully appreciated. Part of the data utilized in this publication were obtained and made available by The MIT-UHI-IRTF Joint Campaign for NEO Reconnaissance. The MIT component of this work is supported by the National Science Foundation under Grant No. 0506716. K.J.W. is grateful for funding from NASA’s OPR program.

REFERENCES

Barucci, M. A., Cheng, A. F., Michel, P., et al. 2011, Exp. Astron. Binzel, R. P., Harris, A. W., Bus, S. J., & Burbine, T. H. 2001, Icarus, 151, 139 Binzel, R. P., Rivkin, A. S., Stuart, J. S., et al. 2004, Icarus, 170, 259 Bottke, W. F., Morbidelli, A., Jedicke, R., et al. 2002, Icarus, 156, 399 Bottke, W. F., Vokrouhlický, D., & Nesvorný, D. 2007, Nature, 449, 48 Botte, W. F., Jr., Vokrouhlický, D., Rubincam, D. P., & Nesvorný, D. 2006, Annu. Rev. Earth Planet. Sci., 34, 157 Bus, S. J. 1999, PhD thesis, Massachusetts Institute of Technology Campins, H., Morbidelli, A., Tsiganis, K., et al. 2010, ApJ, 721, L53 Christou, A. A. 2003, Planet. Space Sci., 51, 221 Clark, B. E., Binzel, R. P., & Howell, E. S. 2011, Icarus, 216, 462 Clark, B. E., Ziffer, J., Nesvorný, D., et al. 2010, J. Geophys. Res. (Planets), 115, 6005 Cloutis, E. A., Hudon, P., Romanek, C. S., et al. 2010, Meteorit. Planet. Sci., 45, 1668 Cohen, M., Walker, R. G., Carter, B., et al. 1999, AJ, 117, 1864 Cohen, M., Witteborn, F. C., Walker, R. G., Bregman, J. D., & Wooden, D. H. 1995, AJ, 110, 275 Delbo’, M., Dell’Oro, A., Harris, A. W., Motolla, S., & Mueller, M. 2007, Icarus, 190, 236 Delbo’, M., & Harris, A. W. 2002, Meteorit. Planet. Sci., 37, 1929 Delbo’, M., Walsh, K., Mueller, M., Harris, A. W., & Howell, E. S. 2011, Icarus, 212, 138 De León, J., Campins, H., Tsiganis, K., Morbidelli, A., & Licandro, J. 2010, A&A, 513, A26 De León, J., Mothé-Diniz, T., Licandro, J., Pinilla-Alonso, N., & Campins, H. 2011, A&A, 530, L12 DeMeo, F. E., Binzel, R. P., Slivan, S. M., & Bus, S. J. 2009, Icarus, 202, 160 Deutsch, L. K., Hora, J. L., Adams, J. D., & Kassis, M. 2003, Proc. SPIE, 4841, 106 Emery, J. P., Fernández, Y. R., Kelley, M. S., et al. 2010, Lunar and Planetary Institute Science Conference Abstracts, 41, 2282 Harris, A. W. 1998, Icarus, 131, 291 Harris, A. W. 2006, in IAU Symp. 229, ACM 2005, ed. D. Lazzaro, S. Ferraz-Mello, & J. A. Fernández (Cambridge: Cambridge Univ. Press), 449 Harris, A. W., Fahnestock, E. G., & Pravec, P. 2009, Icarus, 199, 310 Hiroi, T., Jenniskens, P., Bishop, J. L., et al. 2010, Meteorit. Planet. Sci., 45, 1836 Hiroi, T., Zolensky, M. E., Pieters, C. M., & Lipschutz, M. E. 1996, Meteorit. Planet. Sci., 31, 321 Howell, S. B. 1989, PASP, 101, 166 Jenniskens, P., Shaddad, M. H., Numan, D., et al. 2009, Nature, 458, 485 Jenniskens, P., Vaubaillon, J., Binzel, R. P., et al. 2010, Meteorit. Planet. Sci., 45, 1590 Johnston, W. R., Richardson, D. C., & Walsh, K. J. 2010, NASA Planetary Data System, 128
Kassis, M., Adams, J. D., Hora, J. L., Deutsch, L. K., & Tollestrup, E. V. 2008, 
FASP, 120, 1271
Lagage, P. O., Pel, J. W., Authier, M., et al. 2004, Messenger, 117, 12
Landolt, A. U. 1973, AJ, 78, 959
Lauretta, D. S., Drake, M. J., Benzel, R. P., et al. 2010, Meteorit. Planet. Sci. 
Suppl., 73, 5153
Morbidelli, A., & Nesvorny, D. 1999, Icarus, 139, 295
Mottola, S., & Lahulla, F. 2000, Icarus, 146, 556
Mueller, M., Delbo', M., Hora, J. L., et al. 2011, AJ, 141, 109
Mueller, M., Harris, A. W., & Fitzsimmons, A. 2007, Icarus, 187, 611
Nolan, M. C., Magri, C., Ostro, S. J., et al. 2007, BAAS, 38, 433
Ostro, S. J., Margot, J.-L., Benner, L. A. M., et al. 2006, Science, 314, 
1276
Perozzi, E., Rossi, A., & Valsecchi, G. B. 2001, Planet. Space Sci., 49, 3
Pravec, P., Šarounová, L., Rabinowitz, D. L., et al. 2000, Icarus, 146, 190
Pravec, P., Scheirich, P., Kušnirák, P., et al. 2006, Icarus, 181, 63
Scheeres, D. J. 2007, Icarus, 189, 370
Scheirich, P., & Pravec, P. 2009, Icarus, 200, 531
Tholen, D. J. 1989, in Asteroids II, ed. R. P. Binzel, T. Gehrels, & M. S. Matthews 
(Tucson, AZ: Univ. Arizona Press), 1139
Walsh, K. J., Richardson, D. C., & Michel, P. 2008, Nature, 454, 188
Wolters, S. D., Rozitis, B., Duddy, S. R., et al. 2011, MNRAS, 418, 1246