The binary near-Earth asteroid (175706) 1996 FG_3 — An observational constraint on its orbital stability

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Proposed running head: Binary near-Earth asteroid 1996 FG_3

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Abstract

Using our photometric observations taken between April 1996 and January 2013 and other published data, we derive properties of the binary near-Earth asteroid (175706) 1996 FG_3 including new measurements constraining evolution of the mutual orbit with potential consequences for the entire binary asteroid population. We also refined previously determined values of parameters of both components, making 1996 FG_3 one of the most well understood binary asteroid systems. With our 17-year long dataset, we determined the orbital vector with a substantially greater accuracy than before and we also placed constraints on a stability of the orbit. Specifically, the ecliptic longitude and latitude of the orbital pole are 266° and −83°, respectively, with the mean radius of the uncertainty area of 4°, and the orbital period is 16.1508 ± 0.0002 h (all quoted uncertainties correspond to 3σ). We looked for a quadratic drift of the mean anomaly of the satellite and obtained a value of 0.04 ± 0.20 deg/yr^2, i.e., consistent with zero. The drift is substantially lower than predicted by the pure binary YORP (BYORP) theory of McMahon and Scheeres (McMahon, J., Scheeres, D. [2010]. Icarus 209, 494–509) and it is consistent with the theory of an equilibrium between BYORP and tidal torques for synchronous binary asteroids as proposed by Jacobson and Scheeres (Jacobson, S.A., Scheeres, D. [2011]. ApJ Letters, 736, L19). Based on the assumption of equilibrium, we derived a ratio of the quality factor and tidal Love number of $Q/k = 2.4 \times 10^5$ uncertain by a factor of five. We also derived a product of the rigidity and quality factor of $\mu Q = 1.3 \times 10^7$ Pa using the theory that assumes an elastic response of the asteroid material to the tidal forces. This very low value indicates that the primary of 1996 FG_3 is a 'rubble pile', and it also calls for a re-thinking of the tidal energy dissipation in close asteroid binary systems.

Key words: Asteroids, dynamics; Near-Earth objects; Photometry

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1 Introduction

The near-Earth asteroid (175706) 1996 FG_3 (hereafter referred to as FG3) was discovered by R.H. McNaught from Siding Spring on 1996 March 24. Its binary nature was revealed by Pravec et al. (1998). The asteroid was observed thoroughly with a variety of techniques during six apparitions from 1996 to 2013. Our photometric dataset represents the longest coverage obtained for a binary near-Earth asteroid so far, providing a unique opportunity to study an evolution of the mutual orbit of components of a small binary asteroid. Moreover, a detailed understanding of this asteroid system is motivated by its accessibility from the Earth with a delta-V requirement of 5.16 km/s (Binzel et al., 2004) and so it is a popular candidate for past and future proposed space missions.

There have been a number of recent observations and models of this binary published in the literature, however rather than reviewing them here, we will delay their review until after we present our new data. Then in Section 3, we can present and discuss all of the system parameters including previously published and those updated from our work.

The structure of this paper is as follows. In Section 2, we present a model of the mutual orbit of the components of FG3 constructed from our complete photometric dataset 1996–2013. Then in Section 3, we summarize all known parameters of the binary, updating them using our new data where needed. In Section 4, we then discuss implications of the current known characteristics of the binary, especially on the BYORP theory from the derived low upper limit on the binary's orbital drift.

2 Model of the mutual orbit

2.1 Observational data

The data used in our analysis, obtained during six apparitions, are summarized in Table 1. The references and descriptions of observational procedures of the individual observatories are summarized in Table 2.

The data were reduced using the standard technique described in Pravec et al. (2006). By fitting a two-period Fourier series to data points outside mutual (occultation or eclipse) events, the rotational lightcurves of the primary (short-period) and the secondary (long-period), which are additive in intensities, were separated. The long-period component containing the mutual events and the secondary rotation lightcurve is then fitted in subsequent numerical modeling (Sect. 2.2).

A special approach was needed for the 2013 data where the primary rotational lightcurve was incompletely described by the actual observations. Using a shape and rotation model for the primary that we obtained from data from the previous

Table 1
Observations

Time span	No. of nights	Telescope	References
1996-04-09 to 1996-04-21	10	0.6-m Bochum	ML00
1998-12-03 to 1999-01-09	8	0.65-m Ondřejov	P00
	4	1.23-m Calar Alto	ML00
	3	0.7-m Kharkiv	P00
	3	0.61-m TMO	P00
	1	1.55-m Catalina	P00
2009-04-12 to 2009-04-17	4	0.65-m Ondřejov	This work
	1	0.5-m Carbuncle Hill	This work
2010-12-14 to 2011-02-09	5	1.23-m Calar Alto	This work
	3	3.5-m Apache Point	This work
	2	2.2-m UH	This work
2011-11-23 to 2012-02-12	4	0.5-m Sugarloaf Mt.	This work
	3	0.46-m Wise Obs.	This work
	3	0.7-m Abastumani	This work
	3	2.1-m Kitt Peak	This work
	2	0.7-m Kharkiv	This work
	2	0.65-m Ondřejov	This work
	2	0.6-m TRAPPIST	This work
	1	0.6-m Modra	This work
	1	0.41-m PROMPT	This work
	1	0.36-m Via Capote	This work
	1	0.82-m IAC-80	This work
2013-01-05 to 2013-01-07	3	2.1-m Kitt Peak	This work

References: ML00 (Mottola and Lahulla, 2000), P00 (Pravec et al., 2000),

apparitions, we generated a synthetic rotational lightcurve of the primary and subtracted it from the data to obtain the long-period component of the lightcurve on the three nights in January 2013.

2.2 Numerical model

We have constructed a model of the binary using the technique of Scheirich and Pravec (2009) that we further developed and enhanced in this work. In the following, we outline the basic points of the method, but we refer the reader to the 2009 paper for details of the technique. We also describe new features and improvements of the method that we developed recently.

The shapes of the components were represented with ellipsoids, orbiting each other on a Keplerian orbit with apsidal precession, and allowing for a quadratic drift in

Table 2
Observational stations

Telescope	Observatory	References for observational and reduction procedures
3.5-m Apache Point	Apache Point Observatory, New Mexico, USA	1
2.2-m UH	University of Hawaii, USA	2
2.1-m Kitt Peak	Kitt Peak, Arizona, USA	1
1.55-m Catalina	Catalina Observatory, Arizona, USA	P00
1.23-m Calar Alto	Calar Alto, Spain	ML00
0.82-m IAC-80	Instituto de Astrofísica de Canarias, Spain	TR10
0.7-m Abastumani	Abastumani Astrophysical Observatory, Georgia	K02, Pi12
0.7-m Kharkiv	Kharkiv National University, Ukraine	1998/1999: K02, 2011/2012: P12
0.65-m Ondřejov	Ondřejov, Czech Republic	1998/1999: P00, 2009-2012: P06
0.61-m TMO	Table Mountain Observatory, California, USA	P00
0.60-m Bochum	La Silla, Chile	ML00
0.6-m Modra	Modra, Slovakia	G07
0.6-m TRAPPIST	La Silla, Chile	P14
0.5-m Carbuncle Hill	Carbuncle Hill Observatory, Massachusetts, USA	WP09
0.5-m Sugarloaf Mt.	Sugarloaf Mountain Observatory, Massachusetts	W13
0.46-m Wise Obs.	Wise Observatory, Israel	B08, PB09
0.41-m PROMPT	Cerro Tololo, Chile	P12
0.36-m Via Capote	Via Capote Observatory, California, USA	P12

References: 1 – The data were reduced using IRAF and the PHOT package, following the methods by Harris and Lupishko (1989). 2 – The observations were obtained using Tektronix 2048 × 2048 CCD camera at the f/10 focus of the telescope (image scale of 0.219” pixel^{-1}) through Kron-Cousins filter R.
B08 (Brosch et al., 2008), G07 (Galád el al., 2007), K02 (Krugy et al., 2002), ML00 (Mottola and Lahulla, 2000), P00 (Pravec et al., 2000), P12 (Pravec et al., 2012, Supplementary Material), P14 (Pravec et al. 2014), PB09 (Polishook and Brosch, 2009), Pi12 (Pilcher et al. 2012), TR10 (Trigo-Rodríguez et al., 2010), W13 (Warner et al., 2013), WP09 (Warner and Pray, 2009).

mean anomaly.

The primary was modeled as an oblate spheroid, with its spin axis assumed to be normal to the mutual orbital plane of the components. The shape of the secondary was taken as a prolate spheroid in synchronous rotation, with its long axis aligned with the centers of the two bodies. The shapes were approximated with 1016 and 252 triangular facets for the primary and the secondary, respectively. The components were assumed to have the same albedo. The brightness of the system as seen by the observer was computed as a sum of contributions from all visible facets using a ray-tracing code that checks which facets are occulted by or are in shadow from the other body. A combination of Lommel-Seeliger and Lambert scattering laws was used (see, e.g., Kaasalainen et al., 2002).

The quadratic drift in mean anomaly, ΔM_d, was fitted as an independent parameter. It is the coefficient in the second term of the expansion of the time-variable mean anomaly:

$$M(t) = M(t_0) + n(t - t_0) + \Delta M_d(t - t_0)^2, \tag{1}$$

where

$$\Delta M_d = \frac{1}{2}\dot{n}, \tag{2}$$

where n is the mean motion, t is the time, and t_0 is the epoch.

ΔM_d was stepped from -3 to $+3$ deg/yr^2 with a step of 0.02 deg/yr^2, and all other parameters were fitted at each step.

We also tested a possibility of a larger value of ΔM_d that would cause an integer change of the number of orbital cycles between the 1998-1999 and the 2009 apparitions, but we found such large orbital drifts entirely incompatible with the data.

To reduce the complexity of the model, we estimated an upper limit on the eccentricity of the mutual orbit by fitting the data from the best covered apparition 2011-2012. The model includes a precession of the line of apsides. The pericenter drift rate depends on the polar flattening of the primary (see Murray and Dermott, 1999, Eq. (6.249)), but the polar flattening is poorly constrained from the data (see Table 3), so instead we fit the drift rate as an independent parameter. Its initial values were stepped in a range from zero to 35°/day. This range encompasses all plausible values for the flattening of the primary and other parameters of the system.

Since the upper limit on eccentricity of the mutual orbit was found to be low ($e_{\max} = 0.07$), in modeling data from all apparitions together, we set the eccentricity equal to zero for simplicity. This assumption had a negligible effect on the accuracy of other derived parameters of the binary model. [1]

Across all observations, we found a unique solution for the system parameters, see Table 3. We describe and discuss these parameters in Section 3.

Examples of the long-period component data together with the synthetic lightcurve of the best-fit solution are presented in Fig. 1. An uncertainty area of the orbital

[1] We tested an effect of the zero eccentricity assumption with a following experiment: We generated synthetic lightcurve data for the binary system with forcing its eccentricity to be 0.07. Then we modeled the data with the assumption of circular orbit. We found that there were only minor or negligible differences in the fitted parameters; the largest difference of 5% was in the semimajor axis.

pole is shown in Fig. 2.

We estimated realistic uncertainties of the fitted parameters using the procedure described in Scheirich and Pravec (2009). For each parameter, we obtained its admissible range that corresponds to a 3-σ uncertainty.

We also attempted to model the shape and spin of the primary using the lightcurve inversion method of Kaasalainen and Torppa (2001) and Kaasalainen et al. (2001) with the data for the primary lightcurve (outside the mutual events and with the secondary's rotational component subtracted) from the five apparitions 1996–2012. We found that a unique solution for the shape and pole of the primary could not be obtained, with a wide range of shapes and poles that produced equally good fits to the data. Apparently, the ambiguity is due to the combination of two features: (1) The primary's shape irregularities are low, the shape does not differ from oblate spheroid much. (2) Due to the asteroid's obliquity being close to 180 degrees, the object was observed at near-equator on aspects only. Assuming zero inclination of the mutual orbit of the components to the primary's equator, i.e., the primary's pole being the same as the orbital pole, we obtained a unique solution for the primary rotational period of 3.595195 ± 0.000003 h (3-σ uncertainty; this includes also the uncertainty of the orbital pole of 4 degrees). Nevertheless, even for the constrained pole, the primary's shape was not derived uniquely, as the polar flattening of the primary is poorly defined with the observations at near-equator on aspects.

3 Parameters of 1996 FG_3

In this section, we summarize known parameters of the binary asteroid. We overview previous publications and we also derive or refine some parameters using our newest data. In Table 3, we provide the best estimated values for the parameters of FG3.

In the first part of the table, we present data derived from optical, thermal and spectroscopic observations of the system. H_V and G are the mean absolute magnitude and the phase parameter of the H–G phase relation (Bowell et al., 1989), $V - R$, $R - I$ and $B - V$ are the asteroid's color indices in the Johnson-Cousins photometric system, $D_{\rm eff}$ is the effective diameter of system, $p_{\rm V}$ is the visual geometric albedo and Γ is the thermal inertia of the asteroid surface.

The best values for these parameters, except for the color indices that were measured by Pravec et al. (2000), were obtained by Wolters et al. (2011). They took thermal and visual observations of the asteroid using the ESO VLT and NTT, respectively. They combined their visual photometric data with measurements by Pravec et al. (2000) and Mottola and Lahulla (2000) and, thanks also to their measurement taken at the small solar phase of 1.4 deg, they obtained the most precise value for the mean absolute magnitude of the system. The previous H_V value by Pravec et al. (2000) is in agreement to about 2σ. We have checked it also with our recent absolute photometry from Ondřejov in April 2009 and December 2011 (Table 1), and we found an agreement with the H, G values by Wolters et al. (2011) to a few hundredths of magnitude. With the precise H, G values, Wolters et al. (2011) then

Table 3
Properties of binary asteroid (175706) 1996 FG_3.

Parameter	Value	Unc.	Reference
Whole system:			
H_V	17.833 ± 0.024	1σ	W11
G	-0.041 ± 0.005	1σ	W11
$V - R$	0.380 ± 0.003	1σ	P00
$R - I$	0.334 ± 0.003	1σ	P00
$B - V$	0.708 ± 0.005	1σ	P00
D_{eff} (km)	1.71 ± 0.07	1σ	W11
p_V	0.044 ± 0.004	1σ	W11
Γ (J m^{-2} K^{-1} s$^{-1/2}$)	120 ± 50	1σ	W11
Taxon. class	C, B, Xc		B01, W12, P13
Spectrum	Featureless and flat in visible range.		B01
	Shallow features near 1.2 and 2.0 μm.		W12
	Abs. band of OH or waterbearing mineral.		R13
Meteorite analogue	CM2, CM, C2		L11, P12, P13
Primary:			
$D_{1,\mathrm{C}}$ (km)	1.64 ± 0.20	3σ	this work
$D_{1,\mathrm{V}}$ (km)	$1.69^{+0.24}_{-0.21}$	3σ	this work
P_1 (h)	3.595195 ± 0.000003	3σ	this work
$(A_1B_1)^{1/2}/C_1$	$1.2^{+0.5}_{-0.2}$	3σ	this work
A_1/B_1	1.06 ± 0.03	3σ	P06
$\rho_1 = \rho_2$ (g cm^{-3})	1.3 ± 0.5	3σ	this work
Secondary:			
$D_{2,\mathrm{C}}/D_{1,\mathrm{C}}$	0.29 ± 0.02	3σ	this work
$D_{2,\mathrm{C}}$ (km)	0.48 ± 0.07	3σ	this work
$D_{2,\mathrm{V}}$ (km)	(0.49 ± 0.08)	3σ	this work
P_2 (h)	16.15 ± 0.01	1σ	P06
A_2/B_2	1.3 ± 0.2	3σ	this work
Mutual orbit:			
$a/D_{1,\mathrm{C}}$	$1.5^{+0.3}_{-0.2}$	3σ	this work
$(L_\mathrm{P}, B_\mathrm{P})$ (deg.)	$(266, -83) \pm 4^a$	3σ	this work
P_{orb} (h)	16.1508 ± 0.0002	3σ	this work
$e_{\max}$	0.07	3σ	this work
ΔM_d (deg/yr^2)	0.04 ± 0.20	3σ	this work
$\dot{P}_{\mathrm{orb}}$ (h/yr)	-0.000007 ± 0.000033	3σ	this work
$\dot{a}$ (cm/yr)	-0.07 ± 0.34	3σ	this work

References: B01 (Binzel et al., 2001), L11 (de León et al., 2011), P00 (Pravec et al., 2000), P06 (Pravec et al., 2006), P12 (Popescu et al., 2012), P13 (Perna et al., 2013), R13 (Rivkin et al., 2013), W11 (Wolters et al., 2011), W12 (Walsh et al., 2012).

[a] This is the mean radius of the uncertainty area; see its actual shape in Fig. 2.

applied the Advanced Thermophysical Model (ATPM) to their thermal observations and derived the effective diameter, geometric albedo and thermal inertia. They assessed realistic uncertainties of the derived parameters.

The effective diameter and geometric albedo were derived also in two other recent works Mueller et al. (2011) and Walsh et al. (2012). Mueller et al. reported $p_V = 0.042^{+0.035}_{-0.017}$ and $D_{\rm eff} = 1.84^{+0.56}_{-0.47}$ and Walsh et al. derived $p_V = 0.039 \pm 0.012$ and $D_{\rm eff} = 1.90 \pm 0.28$ km. Their values are in agreement with those by Wolters et al. (2011), but they are less precise, because both teams observed the asteroid at high phase angles $> 50°$ and they used the NEATM in their modeling. The NEATM is less accurate than the ATPM, and for data obtained at high phase angles it systematically overestimates diameter and underestimates albedo (Wolters and Green, 2009). We adopt the values derived by Wolters et al. (2011) as the most precise data for these parameters.

In the most recent work on this topic, Yu et al. (2014) combined the observational data from the already mentioned publications and other sources. From this dataset, they attempted to further refine these photometric and thermal parameters. While the thermal modeling part of their paper is well done, their work suffers because they did not properly assess the real uncertainties of their spin and shape model, which they constructed from an extremely limited dataset. Though their derived values for the photometric and thermal parameters are close to those of Wolters et al. (2011), we hesitate to utilize their values due to the incomplete assessment of their uncertainties. Thus, we continue to use the parameters of Wolters et al. (2011), where the uncertainties were properly estimated.

Several works have been published reporting spectroscopic observations of FG3 in the visible and near-infrared spectral range, see the references in Table 3. The obtained data generally agree with featureless and flat spectrum in the visible range. There are differences in the near-infrared range and some authors report shallow features indicating presence of olivine, pyroxene and OH or water-bearing minerals.

Although there is no consensus on taxonomic classification of FG3 in the literature (Binzel et al., 2001; de León et al., 2011; Walsh et al., 2012), they agree that the asteroid is composed of primitive material, and all the proposed taxonomic classes are consistent with the measured low geometric albedo.

In the next two parts of Table 3, we give parameters for the components of the binary. The indices 1 and 2 refer to the primary and the secondary, respectively. $D_{i,\rm C}$ is the cross-section equivalent diameter, i.e., the diameter of a sphere with the same cross section, of the i-th component at the observed, i.e., equator-on aspect. $D_{i,\rm V}$ is the volume equivalent diameter, i.e., the diameter of a sphere with the same volume, of the i-th component. $D_{2,\rm C}/D_{1,\rm C}$ is the ratio between the cross-section equivalent diameters of the components. P_i is the rotational period of the i-th component. $(A_1B_1)^{1/2}/C_1$ is a ratio between the mean equatorial and the polar axes of the primary. A_i/B_i is a ratio between the equatorial axes of the i-th component (equatorial elongation). $\rho_1 = \rho_2$ are the bulk densities of the two components, which we assumed to be the same in our modeling.

Most of the quantities were parameters of our model given in Section 2.2 and we derived them from our observations. The cross-section and volume equivalent diameters of the components were derived using the D_{eff} value from Wolters et al. (2011) for the absolute size calibration of our model, assuming the same geometric albedo for both components. The uncertainties for all the parameters are realistic, corresponding to 3σ, except for $D_{2,\mathrm{V}}$ where there may be present a systematic error due to the assumed shape of prolate ellipsoid ($B_2 = C_2$), so we give the value in parentheses.

The asteroid FG3 was observed with the Arecibo and Goldstone radars by Benner et al. (2012). They reported a rounded, slightly elongated shape of the primary with diameter of about 1.8 km, with features along its equator resembling that of the equatorial ridge of binary asteroid (66391) 1999 KW_4 (Ostro et al., 2006). They also mentioned that their data suggested a synchronous rotation of the secondary. These preliminary estimates from the radar observations are in agreement with our data, especially considering that their estimated primary diameter corresponds to the equatorial rather than volume-equivalent diameter.

In the last part of Table 3, we summarize the parameters of the mutual orbit of the binary components. a is the semimajor axis, $L_{\mathrm{P}}, B_{\mathrm{P}}$ are the ecliptic coordinates of the orbital pole in the equinox J2000, P_{orb} is the orbital period, e_{max} is the upper limit on eccentricity, and ΔM_d is the quadratic drift in mean anomaly. We also give the time derivatives of the orbital period and the semimajor axis, derived from ΔM_d.

Earlier works where some of the binary parameters were derived are Pravec et al. (2000), Mottola and Lahulla (2000), Pravec et al. (2006) and Scheirich and Pravec (2009). Their results are generally in agreement with our current best estimated parameters, though naturally their values were less precise because they were derived from the observations from the first two apparitions only.

The binary (175706) 1996 FG_3 appears to be a typical near-Earth binary asteroid according to most of its parameters. It is an apparent outlier in only one thing, plus related quantities: its primitive taxonomic type and composition. Most known NEA binaries are S and other rocky types. However, it may be only a bias due to the well known observational selection effect against dark-albedo NEAs; primitive-type binaries might be actually as common as those of S and similar types. Probably related to its primitive composition is also its relatively low bulk density of $\sim$ 1.3 g cm^{-3}. A consequence of it appears to be also its relatively long primary rotation period of 3.6 h; the primary periods of NEA binaries concentrate between 2.2 and 2.8 h (Pravec et al., 2006), but the FG3 primary rotates more slowly for the lower critical spin frequency for its low bulk density. Indeed, the normalized total angular momentum content of FG3 is $\alpha_L = 1.00 \pm 0.08$ (1-σ uncertainty), i.e., in the range 0.9–1.3 for small near-Earth and main belt asteroid binaries and exactly as expected for the proposed formation of small binary asteroids by fission of critically spinning rubble-pile progenitors (Pravec and Harris, 2007).

4 Implications for the BYORP effect and tidal parameters

While most of the parameters of the binary FG3 were known, albeit with lower accuracy, from earlier publications, we study the secular change of the mutual orbit for the first time. We have found that there is a very low or zero drift of the orbit over the observational interval of 17 years. It is interesting to compare this observation with theory of the binary YORP (BYORP).

The BYORP effect is a secular change of the mutual orbit of a binary asteroid system with a synchronous satellite due to the emission of thermal radiation from the asymmetric shape of that satellite. It was first hypothesized by Ćuk and Burns (2005) after the prediction of two other radiative torques: the Yarkovsky and YORP effects (see the review by Bottke et al., 2006). Both of these torques have been observed acting on asteroid systems as expected according to the theory: the Yarkovsky effect was first detected by Chesley et al. (2003) on 6489 Golevka and the YORP effect was first detected by Lowry et al. (2007) and Taylor et al. (2007) on 54509 (2000 PH_5), and Kaasalainen et al. (2007) on (1862) Apollo. The BYORP effect is identical to the YORP effect except the lever arm of the radiative torque extends from the surface elements of the satellite to the center of mass of the mutual orbit rather than to the center of mass of the asteroid itself. Using the YORP effect as a guide, McMahon and Scheeres (2010a,b) built a detailed theory of the secular evolution of the mutual orbit due to the BYORP effect, which predicts that it causes the orbit to expand or contract on a timescale of thousands of years, as long as the satellite remains synchronous. Specifically, they applied this theory to the binary near-Earth asteroid 1999 KW4 for which a detailed model (e.g. mutual orbit and asteroid shapes) is available (Ostro et al., 2006). From this example, they derived formulae to scale their results for application to other binary asteroid systems. They showed that the BYORP effect can be detected in the system by tracking mean anomaly which grows quadratically in time for a contracting or expanding mutual orbit.

The mean anomaly of changing orbit expanded to the second degree in time is expressed by Equations (1) and (2). ΔM_d can be expressed using a semimajor axis of the mutual orbit a and its time derivative as

$$\Delta M_d = \frac{1}{2}\dot{n} = -\frac{3n\dot{a}}{4a}. \tag{3}$$

McMahon and Scheeres (2010b) derived a current semi-major axis expansion rate for 1999 KW_4 of $\dot{a}_{\mathrm{KW4}} \sim 7$ cm per year. Pravec and Scheirich (2010) adapted their scaling to use with parameters that were straightforwardly derived or estimated from photometric observations for other observed binary asteroids. The adapted formulas are as follows:

$$\Delta M_d = \frac{K}{\sqrt[3]{q(1+q)}D_1^2\rho^{\frac{4}{3}}P_{\mathrm{orb}}^{\frac{2}{3}}a_{\mathrm{hel}}^2\sqrt{1-e_{\mathrm{hel}}^2}}, \tag{4}$$

$$K = -24\pi \left(\frac{3\pi}{G}\right)^{\frac{4}{3}} \dot{a}_{\mathrm{KW4}} \frac{a^3_{\mathrm{KW4}} a^2_{\mathrm{hel,KW4}} \sqrt{1 - e^2_{\mathrm{hel,KW4}}}}{(1 + q^{-1}_{\mathrm{KW4}}) D^2_{2,\mathrm{KW4}} P^3_{\mathrm{orb,KW4}}}, \tag{5}$$

where q is the mass ratio between binary components, D_i is the diameter of the i-th body, ρ is the bulk density, P_{orb} is the orbital period, a_{hel} and e_{hel} are the semi-major axis and eccentricity of the binary's heliocentric orbit, and G is the gravitational constant.

Using the above equations, Pravec and Scheirich (2010) predicted the quadratic drift for several binary near-Earth asteroids and identified seven candidates for detection of the BYORP effect within years 2010–2015 (including previous observed apparitions of these systems) using observations with telescopes of sizes about 2 m and smaller: (7088) Ishtar, (65803) Didymos, (66063) 1998 RO_1, (88710) 2001 SL_9, (137170) 1999 HF_1, (175706) 1996 FG_3, and (185851) 2000 DP_{107}. The estimated values of ΔM_d for these systems were from -0.24 to -3.27 deg/yr^2. The value they predicted for 1996 FG_3 was -0.89 deg/yr^2. With the current refined values for the parameters of FG3, the ΔM_d predicted from the BYORP theory would be -1.30 deg/yr^2. Our detected value, 0.04 ± 0.20 deg/yr^2, is much lower than this prediction.

More recently, Jacobson and Scheeres (2011a) presented an improved theory of BYORP where mutual tides between the two components were included for the first time. They showed that a stable long-term equilibrium may exist between these two torques if the BYORP effect is removing angular momentum from the orbit. Since the mean motion of the orbit is slower than the rotation rate of the primary, the satellite raises a tidal bulge on the primary that removes energy from the rotation of the primary and transfers angular momentum to the mutual orbit. These two torques are opposite in sign and can balance one another because they depend differently on the mutual orbit semi-major axis. They evolve the mutual orbit to an equilibrium semi-major axis, where the mutual orbit no longer evolves.

An observation of zero drift in the mean anomaly of the mutual orbit of the binary system may indicate the presence of such equilibrium. Alternatively, the secondary could be very symmetric, thereby suffering a very small BYORP effect torque, or the BYORP theory is incorrect. This last option is unlikely given the success of the other radiative torques: Yarkovsky and YORP.

If the binary asteroid system is in the equilibrium, then it is possible to learn about the interior structure of the primary from the semi-major axis and the tidal torque balance. The BYORP and tidal torques are:

$$\Lambda_B = -\mathcal{B}_2 H_{\mathrm{hel}} R_1^3 a, \tag{6}$$

$$\Lambda_T = \frac{2\pi k \rho \omega_d^2 R_1^5 q^2}{Q a^6}, \tag{7}$$

where $\mathcal{B}_2$ is a constant representing an averaged acceleration in the direction parallel to the motion of the secondary depending only on the shape of the secondary

(McMahon and Scheeres, 2010b), $H_{\rm hel} = (2/3)F_{\rm hel}/(a_{\rm hel}^2\sqrt{1-e_{\rm hel}^2})$, $(2/3)F_{\rm hel} = 6.\bar{6}\times 10^{13}$ kg km s^{-2} is the solar constant including a Lambertian factor, $a_{\rm hel}$ and $e_{\rm hel}$ are heliocentric semimajor axis and eccentricity, a is measured in primary radii R_1, k and Q are the tidal Love number and the quality factor of the primary, $\omega_d = \sqrt{4\pi\rho G/3}$ is the critical angular frequency, ρ is a density of the body, and G is the gravitational constant.

The BYORP coefficient $\mathcal{B}_2$ is a function solely of the shape of the secondary and not dependent on the size of the body. Nominally, the coefficient can have any absolute value between 0 and 2, but it is predicted to be ~ 0.01 for shapes similar to 1999 KW_4 (McMahon and Scheeres, 2010b).

The two tidal parameters k and Q are not well known for any small body. The tidal Love number k represents how strongly the spherical harmonic degree two of the gravity potential of the primary responds to the radial gravitational perturbation of the satellite. More specifically, it is the ratio of the additional potential produced by the deformation of the primary to the original gravitational potential. If the primary did not deform at all (i.e. perfectly rigid), the value of k would be 0, and for a point source perturber, a perfect fluid would have a value of 3/2 (Murray and Dermott, 1999). The Moon and Earth are estimated to have tidal Love numbers of 0.03 and 0.3, respectively (Yoder, 1995). The Love number is expected to decrease with the size of the body as the self-gravity of the body decreases and the body begins to respond more as a monolithic structure than as a fluid. How this variation occurs is unknown and complicated by the tidal Love numbers degeneracy with the tidal parameter Q. This parameter is a quality factor that describes the amount of energy dissipated per cycle over the peak potential energy stored during the cycle. For small bodies this parameter is often assumed to be 100 (Goldreich and Sari, 2009), although it is expected to depend on the size and rheology of the body. Taylor and Margot (2011) placed constraints on the tidal parameters of binary asteroid systems, but these could only be limits to each value since they had to assume the maximum possible value for the tidal evolution time for each binary system found in synchronous orbit. They estimated these tidal parameters in terms of product of the tidal quality factor Q and a rigidity μ, which for solid rock has a value of a few to tens of GPa. For 1996 FG_3, they estimate a $\mu Q = 2.7\times 10^9$ Pa, which is approximately $Q/k = 2.7\times 10^7$. These parameters are otherwise unknown for small bodies.

In the equilibrium, the torques Λ_B and Λ_T balance each other and the unknown parameters $\mathcal{B}_2$, k and Q can be directly, though degenerately, determined:

$$\frac{\mathcal{B}_2 Q}{k} = \frac{2\pi\rho\omega_d^2 R_1^2 q^{4/3}}{H_{\rm hel} a^7}. \tag{8}$$

Assuming 1996 FG_3 is in the equilibrium state, we got a value of $\mathcal{B}_2 Q/k = 2.4\times 10^3$ for the nominal values of the parameters on the right-hand side of Eq. 8, with 3σ uncertainty within a factor of two. The tidal-BYORP equilibrium provides a method to directly assess these tidal parameters for the first time given an estimate for the BYORP coefficient of the secondary $\mathcal{B}_2$. It is worth emphasizing that $\mathcal{B}_2$

is only a function of the shape of the secondary, so it is possible to make an estimate of this value from remote sensing alone. Given radar shape models of the secondary of 1999 KW_4, the best estimate of $\mathcal{B}_2$ is approximately 2×10^{-2} (McMahon and Scheeres, 2010b). Considering that this estimate is based on another asteroid's shape, its uncertainty is difficult to assess, but McMahon and Scheeres (2013) have estimated BYORP coefficients from generic asteroid shapes to be between 0 and 5×10^{-2}. As a zeroth order estimate, we use $\mathcal{B}_2 = 10^{-2}$ with a factor of five uncertainty. Therefore, $Q/k = 2.4 \times 10^5$ and with the tidal-BYORP equilibrium it is possible to measure interior structure properties of the FG3 primary from remote sensing.

The Q/k derived from the tidal-BYORP equilibrium is smaller by a factor of about 10^2 than the upper limit predicted by Taylor and Margot (2011), who assumed a tidal evolution timescale of 10 Myr from a mutual orbit where the semi-major axis is twice the primary radius to the current orbit. Since the tidal evolution timescales are proportional to Q/k, this new value predicts much faster tidal evolution in binary asteroid systems. Although, the mutual orbit did not necessarily evolve as prescribed in Taylor and Margot, if it did so with the new tidal parameters, it would only take approximately 10^5 years. It's worth noting that the semi-major axis of FG3 is only 3 primary radii so the evolution assumed in Taylor and Margot has the secondary moving only 1 primary radii. In the self-consistent theory put forward by Jacobson and Scheeres (2011a), the system did not necessarily evolve from a separation of two primary radii, instead after rotational fission, the mutual orbit stabilized onto an eccentric orbit with a semi-major axis of a few primary radii. If that orbit was interior to 3 R_1, it would evolve outwards and circularize due to tides. If that orbit was exterior, then it would evolve inwards and circularize due to the BYORP effect.

Finally, we look at how the result converts to μQ, the product of the rigidity and quality factor. Using

$$\mu Q = \frac{4}{19} \frac{Q}{k} G \pi R_1^2 \rho^2 \tag{9}$$

from Goldreich and Sari (2009), we obtain $\mu Q = 1.3 \times 10^7$ Pa. While the upper limit on μQ of 2.7×10^9 Pa determined by Taylor and Margot (2011) still maintained the possibility that 1996 FG_3 was pre-dominately solid rock if Q was low, now after directly assessing μQ, we rule out the possibility that 1996 FG_3 is anything but a 'rubble pile' asteroid. It has a rigidity orders of magnitude below that of solid rock even given the uncertainties estimating Q and $\mathcal{B}_2$.

The derived value of μQ is lower by about four orders of magnitude than estimated for, e.g., tumbling asteroids (see Pravec et al., 2014). It calls for a re-thinking of the tidal energy dissipation in close asteroid binary systems. While the present theories of tidal evolution (see Taylor and Margot, 2011, and references therein) assume an elastic response of the asteroid material to the tidal forces, the obtained very low μQ value may indicate a non-elastic behavior due to the large amplitude of the tidal forcing function. For instance, as the acceleration vector at the equator of the FG3 primary changes its direction during rotation of the near-critically spinning primary under the tidal forces from the secondary (see Harris et al., 2009), regolith particles may move. Alternatively, a low-load friction theory (a “tribology theory”) may need to be developed for rubble pile asteroids as suggested by Jacobson and Scheeres (2011b).

5 Conclusions

The near-Earth asteroid (175706) 1996 FG_3 is one of the best characterized small asteroid binary systems. Except for being an apparent outlier with its primitive composition and related quantities, it is a typical member of the population of near-Earth asteroid binaries for most of its parameters. With the unique data from our photometric observations taken during its six apparitions over the time interval of almost 17 years, we constrained the long-term stability of a small binary asteroid orbit for the first time. We found the upper limit on drift of the mutual orbit of its components that is consistent with the theory of Jacobson and Scheeres (2011a) of that synchronous binary asteroids are in a state of stable equilibrium between the BYORP effect and mutual body torques. The derived material parameters indicate that the primary is a ‘rubble pile’, that a tidal evolution of the system is much faster than estimated before, and it also calls for a re-thinking of the tidal energy dissipation in close asteroid binary systems.

Acknowledgements

The work at Ondřejov was supported by the Grant Agency of the Czech Republic, Grants 205/09/1107 and P209/12/0229, and by program RVO 67985815. S. Jacobson would like to acknowledge the NASA Earth and Space Science Fellowship as well as thesis support through the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation. He also would like to acknowledge the assistance of the staffs of both the Kitt Peak National Observatory and the Apache Point Observatories. The work of JĎ was supported by Charles University in Prague, project PRVOUK P45. Operations at Carbuncle Hill Observatory and Sugarloaf Mt. Observatory were supported by a Gene Shoemaker NEO grant from the Planetary Society. D. Polishook is grateful to the AXA research fund for their generous postdoctoral fellowship. TRAPPIST is a project funded by the Belgian Fund for Scientific Research (Fond National de la Recherche Scientifique, F.R. SFNRS) under grant FRFC 2.5.594.09.F, with the participation of the Swiss National Science Foundation (SNF). M. Gillon and E. Jehin are FNRS Research Associates, J. Manfroid is Research Director FNRS. The work at Modra was supported by the Slovak Grant Agency for Science VEGA (Grant 1/0670/13). JL and VAL acknowledges support from the project AYA2012-39115-C03-03 (MINECO).

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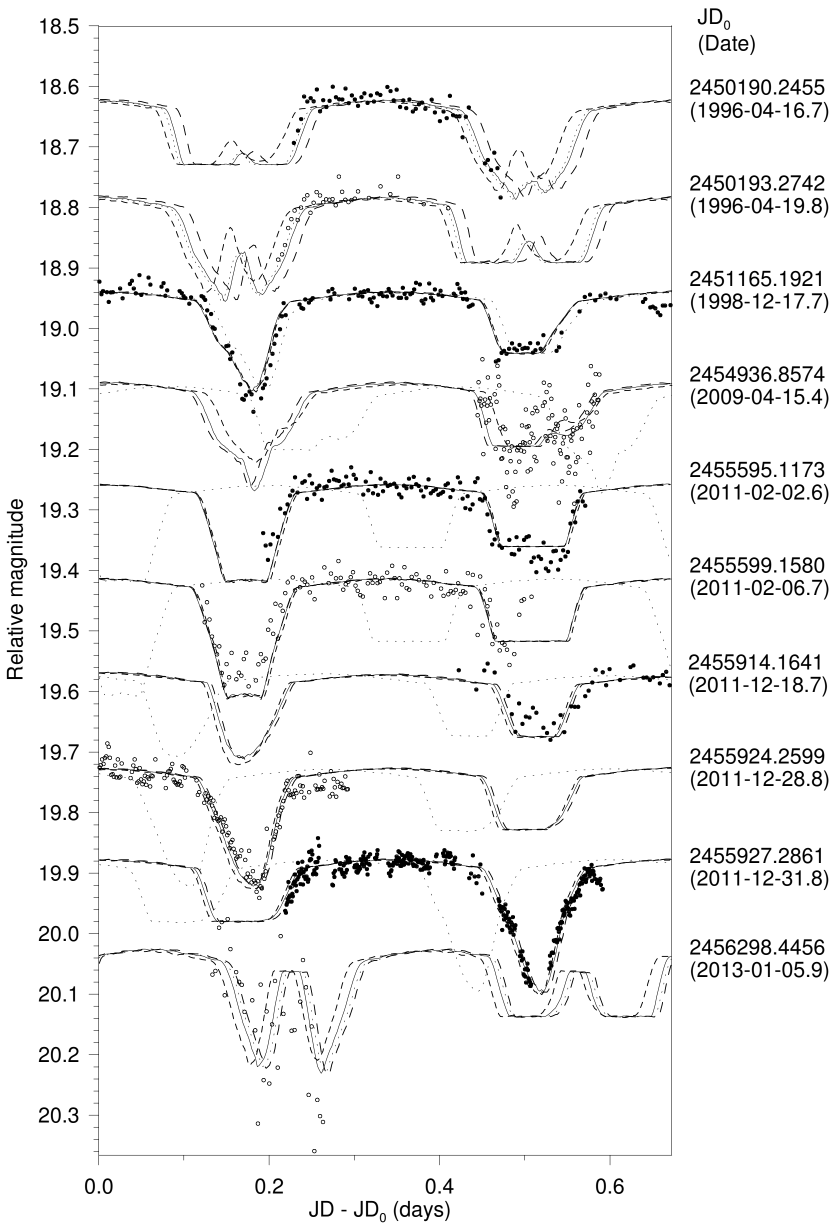

Fig. 1. Selected data of the long-period lightcurve component of 1996 FG_3. The observed data are marked as points. The solid curve represents the synthetic lightcurve of the best-fit solution. The dashed curves are solutions at the 3-σ uncertainty in ΔM_d (short dashes: ΔM_d equal to $+0.24$, long dashes: ΔM_d equal to -0.16 deg/yr^2). For comparison, the dotted curve represents a model with $\Delta M_d = -1.30$ deg/yr^2 as predicted by the pure BYORP theory without tides (see Section 4).

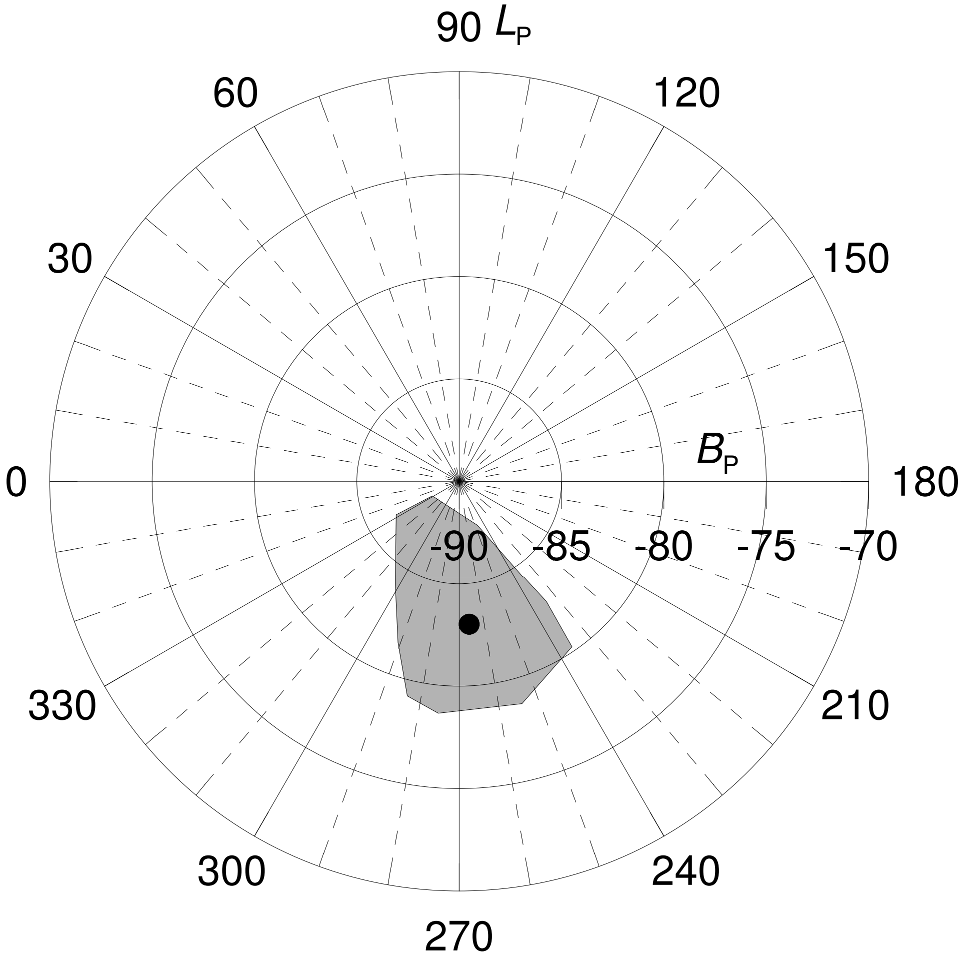

Fig. 2. Area of admissible poles for the mutual orbit in ecliptic coordinates (grey area). The dot is the nominal solution given in Table 3. This area corresponds to 3σ confidence level.