Shape, Thermal and Surface Properties determination of a Candidate Spacecraft Target Asteroid (175706) 1996 FG3

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ABSTRACT

In this paper, a 3D convex shape model of (175706) 1996 FG3, which consists of 2040 triangle facets and 1022 vertices, is derived from the known lightcurves. The best-fit orientation of the asteroid’s spin axis is determined to be λ = 237.7° and β = −83.8° considering the observation uncertainties, and its rotation period is ~3.5935 h. Using the derived shape model, we adopt the so-called advanced thermophysical model (ATPM) to fit three published sets of mid-infrared observations of 1996 FG3 (Wolters et al. 2011; Walsh et al. 2012), so as to evaluate its surface properties. Assuming the primary and the secondary bear identical shape, albedo, thermal inertia and surface roughness, the best-fit parameters are obtained from the observations. The geometric albedo and effective diameter of the asteroid are reckoned to be $p_v = 0.045 \pm 0.002$, $D_{\text{eff}} = 1.69_{-0.05}^{+0.04}$ km. The diameters of the primary and secondary are determined to be $D_1 = 1.63_{-0.04}^{+0.05}$ km and $D_2 = 0.45_{-0.03}^{+0.04}$ km, respectively. The surface thermal inertia $\Gamma$ is derived to be a low value of $80_{-0.76}^{+3.00}$ J m$^{-2}$ s$^{-0.5}$ K$^{-1}$ with a roughness fraction $f_R$ of $0.8_{-0.5}^{+0.7}$. This indicates that the primary possibly has a regolith layer on its surface, which is likely to be covered by a mixture of dust, fragmentary rocky debris and sand. The minimum regolith depth is estimated to be ~5 − 20 mm from the simulations of subsurface temperature distribution, indicating that 1996 FG3 could be a very suitable target for a sample return mission.

Key words: radiation mechanisms: thermal – minor planets, asteroids: individual: (175706)1996FG3 – infrared: general

1 INTRODUCTION

(175706) 1996 FG3 (hereafter, 1996 FG3) is a binary near-Earth asteroid (NEA) belonging to the Apollo type, which has a very low $\Delta V$ value ~5.16 km s$^{-1}$ (Perozzi et al. 2001; Christou 2003). This asteroid was originally chosen as the target for a proposed sample return mission (Barucci et al. 2012), called MarcoPolo-R.

Eclipse events have been observed in the binary system 1996 FG3 in optical wavelengths (Pravec et al. 2000; Mottola & Lahulla 2000). The period of mutual orbit is $16.14 \pm 0.01$ hr, and the diameter ratio $D_2/D_1$ is $0.28_{-0.02}^{+0.01}$ (Scheirich & Pravec 2009). The primary is assumed to be an oblate ellipsoid with a major axis ratio $a/b \sim 1.2$, while the secondary is prolate with a major axis ratio about 1.4. Furthermore, Scheirich & Pravec (2009) showed the rotation period of the primary is ~3.6 hr, and the mass density $1.4_{-0.6}^{+0.5}$ g cm$^{-3}$, where 1996 FG3 is generally classified as a complex C-type (Binzel et al. 2001, 2012; de León et al. 2011, 2013; Rivkin et al. 2013). The optical magnitude and phase coefficient are derived as $H = 17.76 \pm 0.03$ and $g = -0.07 \pm 0.02$ by Pravec et al. (2006), while Wolters et al. (2011) used additional data to derive $H = 17.833 \pm 0.024$ and $g = -0.041 \pm 0.005$. Mueller et al. (2011) obtained an area-equivalent diameter of $1.8_{-0.5}^{+0.6}$ km and a geometric albedo of $p_v = 0.04_{-0.02}^{+0.04}$ for 1996 FG3, based on thermal observations (3.6 and 4.5 μm) from the ”Warm Spitzer” space telescope. Furthermore, Wolters et al. (2011) measured the effective diameter and geometric albedo of the asteroid to be $D_{\text{eff}} = 1.68 \pm 0.25$ km, $p_v = 0.046 \pm 0.014$, $\eta = 1.15$ for a solar phase angle 11.7° from an NEATM (Harris 1998; Delbo & Harris 2002) procedure. In addition, using NEATM method, Walsh et al. (2012) also obtained 1996 FG3's effective diameter and geometric albedo of $D_{\text{eff}} = 1.90 \pm 0.28$ km, $p_v = 0.039 \pm 0.012$, beaming parameter $\eta = 1.61 \pm 0.08$, for a phase angle 67.4°.

Walsh et al. (2008) modeled the formation of the binaries to be a history of rotation acceleration due to the YORP mechanism. Generally, the asymmetric reflection of sunlight...
and asymmetric thermal emission from an asteroid’s surface produces a net force and a net torque. The net force causes the orbit of the asteroid to drift, i.e., Yarkovsky effect, and the net torque alters its rotation period and direction of its rotation axis, i.e., YORP effect (Rozitis & Green 2012). The asymmetric shape of an asteroid, as well as the existence of its finite rotation period and thermal inertia, plays a major role in affecting Yarkovsky and YORP effects. Thermal inertia is an important parameter that controls temperature distribution over the surface and sub-surface of the asteroid, and it is defined by \( \Gamma = \sqrt{\rho c \kappa} \), where \( \rho \) is the mass density, \( \kappa \) the thermal conductivity, and \( c \) the specific heat capacity. According to the definition, thermal inertia depends mainly on the regolith particle size and depth, degree of compaction, and exposure of solid rocks and boulders within the top few centimeters of the surface (Rozitis & Green 2011). Therefore, thermal inertia may act as a vital indicator to infer the presence or absence of loose material on the asteroid’s surface.

The thermal inertia of an asteroid may be evaluated by fitting mid-infrared observations by applying a thermal model to reproduce mid-IR emission curves. Lagerros (1996) proposed a so-called thermophysical model (TPM), which is adopted to calculate infrared emission fluxes as a function of the asteroid’s albedo, thermal inertia, correction factor and so on. For example, we provide several values of \( \Gamma \) for the target of complete/future asteroid missions. On the basis of TPM, Müller et al. (2003) measured the thermal inertia of asteroid (25143) Itokawa to be \( \sim 750 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1} \). Again, Müller et al. (2011) showed that the \( \Gamma \) of 1999 JU3 is likely to be in the range of \( 200 \sim 600 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1} \). The average thermal inertia of 1999 RO36 is estimated to be \( \sim 650 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1} \) (Müller et al. 2012). Recently, Rozitis & Green (2011) proposed an advanced thermophysical model (ATPM) to extensively investigate the thermal nature of the asteroid. Subsequently, Wolters et al. (2011) obtained a best-fit thermal inertia \( \Gamma = 120 \pm 50 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1} \) for 1996 FG3 with ATPM.

The structure of the paper is as follows. Firstly, Section 2 gives a brief introduction to the thermophysical model developed by Rozitis & Green (2011). In Section 3, we concentrate our study on deriving a new 3D shape model for the primary of 1996 FG3 from the known optical lightcurves (Pravec et al. 2000; Mottola & Labella 2004; Wolters et al. 2011). The rotation period and spin axis of the primary are again updated in this work but they appear to be slightly different from those of Scheirich & Pravec (2009). Subsequently, in Section 4, we independently develop computation codes that duplicates ATPM (Rozitis & Green 2011), and then carry out extensive fittings using three sets of mid-infrared observations of 1996 FG3 (Wolters et al. 2011; Walsh et al. 2012) to investigate the primary’s surface physical properties, such as the average thermal inertia, geometric albedo and roughness. The results show that this asteroid may have a very rough surface, in the meanwhile the thermal inertia and geometric albedo seem to be relatively low, indicative of the existence of loose material or regolith spreading over the asteroid’s surface. Moreover, Section 5 deals with the global surface and sub-surface temperature distribution at the aphelion and perihelion, and the minimum depth of regolith layer over the very surface of the primary from the simulations. In final, Section 6 presents the primary results of this work and gives a concise discussion.

2 THEORY METHOD

2.1 Advanced Thermophysical Model

An asteroid is assumed to be a polyhedron composed of \( N \) triangle facets in ATPM. For each facet, the conservation of energy leads to the surface boundary condition (Rozitis & Green 2011)

\[
(1 - A_B)(s_i \psi_i F_{Sun} + F_{scat}) + (1 - A_{th}) F_{red} = \varepsilon \sigma T^4 \bigg|_{z=0} + \left(-\kappa \frac{dT}{dz}\right) \bigg|_{z=0},
\]

where \( A_B \) is the Bond albedo, \( s_i \) indicates whether facet \( i \) is illuminated by the Sun, \( \varepsilon \) is the thermal emissivity, \( \sigma \) the Stefan-Boltzmann constant, \( \kappa \) the thermal conductivity, and \( z \) the depth below the surface, respectively. \( \psi_i \) means a function that returns the cosine of the sunlight incident angle. \( F_{Sun} \) is the integrated solar flux at the distance of the asteroid, which can be approximated by

\[
F_{Sun} = \frac{F_\odot}{r_{\odot AU}^2},
\]

where \( F_\odot \) is the solar constant, about 1367.5 \( \text{Wm}^{-2} \), and \( r_{\odot AU} \) is the heliocentric distance in AU. \( F_{scat} \) and \( F_{red} \) are the total multiple-scattered and thermal-radiated fluxes incident onto the facet from other facets, respectively. \( A_{th} \) is the albedo of the surface at thermal-infrared wavelengths.

Temperature \( T \) can be written as a function of time \( t \) and depth \( z \), i.e., \( T(t, z) \). It can be described by one-dimensional (1D) heat diffusion equation

\[
\rho c \frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}.
\]

For the asteroid, which may have a regolith layer over its surface, the temperature below the surface regolith is supposed to be constant. Thus an internal boundary condition could be given by

\[
\frac{\partial T}{\partial z} \bigg|_{z \to \infty} \to 0.
\]

Theoretically, the temperature distribution can be directly obtained by solving equation (3) and the boundary conditions of equations (1) and (1). However, the surface boundary condition is a nonlinear equation, thus we will attempt to solve them with numerical methods.

In order to simplify the solution of this problem, it is useful to introduce a standard transformation (Spencer & Lebofsky 1989; Lagerros 1996) as follows:

\[
\begin{align*}
x &= \frac{z}{l_s}, \\
\tau &= \omega t, \\
u &= T/T_e,
\end{align*}
\]

where

\[
l_s = \sqrt{\frac{\kappa}{\rho c \omega}}
\]

is referred to as skin depth. And
\[ T_e = \left( \frac{1 - AB}{\varepsilon \sigma} F_{\text{Sun}} \right)^{1/4}, \]  

(5)

called effective temperature.

Thus, the 1D heat diffusion equation is rewritten as

\[ \frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2}, \]  

(6)

while the surface boundary condition and internal boundary condition are converted into

\[ u^i|_{x=0} - \Phi \frac{du}{dx}|_{x=0} = p_1 + p_2 + p_3, \]  

(7)

\[ \frac{\partial u}{\partial x}|_{x \to \infty} \to 0 \]  

(8)

where

\[ p_1 = s \cdot \psi, \]

\[ p_2 = (1 - AB) \frac{F_{\text{scat}}}{\varepsilon \sigma T_e^4}, \]

\[ p_3 = (1 - AB) \frac{F_{\text{rad}}}{\varepsilon \sigma T_e^4} \]

and

\[ \Phi = \frac{\Gamma \sqrt{\varepsilon \sigma}}{\varepsilon \sigma T_e^3}. \]  

(9)

\( \Gamma \) is the thermal inertia, and \( \Phi \) is the thermal parameter.

By numerically solving equation (6) with boundary condition equations (7) and (8), we can acquire the global temperature distribution over the surface and sub-surface of the asteroid. According to the theory, the program codes are also developed for investigation. In the following, we will introduce the results based on numerical calculations.

### 2.2 Emission Flux

On the basis of surface temperature distribution calculated from ATPM, we may estimate thermal infrared fluxes from the asteroid for a given phase angle and a geocentric distance. First of all, a body-fixed coordinate system is established (see Figure 1), where the origin \( O \) locates at the center of asteroid, \( z \)-axis is parallel to its spin axis, and \( x \)-axis is chosen to remain in a plane determined by \( z \)-axis and the line of sun-asteroid, directing towards the Sun.

The direction vector of Earth in the body-fixed system is calculated from the asteroid’s orbit, expressed as \( \vec{n}_E \).

Normal vector of each facet \( \vec{n}_i \) is determined from the shape model of the asteroid. Hence, the view factor of each facet relative to Earth can be evaluated by

\[ f(i) = v(i)A(i) \frac{\vec{n}_i \cdot \vec{n}_E}{\pi \Delta^2}, \]  

(10)

where \( v(i) = 1 \) indicates that facet \( i \) can be seen from Earth, otherwise \( v(i) = 0 \), and \( A(i) \) is the area of facet \( i \).

The flux emitted by each facet is described by the Plank function

\[ B(\lambda, T_e) = \frac{2 \pihc^2}{\lambda^5} \exp \left( \frac{hc}{\lambda \varepsilon \sigma T_e} - 1 \right) \]  

(11)

Consequently, the total fluxes observed from Earth are fully integrated over each facet

\[ F_\lambda = \sum_{i=1}^{N} \varepsilon f(i) B(\lambda, T_i) \]  

(12)

### 3 SHAPE MODEL

According to direct images from space missions and radar measurements, the asteroids in small-size have an irregular shape, while those larger objects appear to be relatively regular shape. For instance, Vesta seems to be more circular than Eros. Considering the asteroid’s rotation, the observed lightcurves change with a lot of extrema, which provide key information on modeling its shape and morphology. Hence, the substantial shape and spin status of the asteroid can be derived from the observations. Kaasalainen & Torppa (2001) and Kaasalainen et al. (2001) developed the lightcurve inverse scheme, and in their model, the inverse problem is perfectly solved using modern deconvolution method and optimization techniques. With the assistance of the optical data, a convex shape of asteroid will be obtained. After repeating the fitting of the convex shape and additional observations, an improved shape of the asteroid will be better constructed. The relative chi-square is defined as

\[ \chi^2_{rel} = \sum_i \left( \frac{L_{\text{obs}}^i - \bar{L}^i}{\bar{L}^i} \right)^2, \]  

(13)

where \( L^i \) and \( \bar{L}^i \) are the modeled and observed brightness from lightcurves, respectively. \( \bar{L}^i_{\text{obs}} \) and \( \bar{L}^i \) are the averaged brightness of the observed data and the model, respectively. At the end of iteration, chi-square will approach a tiny value. Usually, for an asteroid, there are a great many of observations with respect to various solar angles at different epochs. Therefore, such method will yield a reliable result for the shape model.

As 1996 FG3 is a binary asteroid, the values of the brightness in the lightcurves consist of dual contributions coming from the primary and secondary. Similar characteristic of the lightcurves is shown by 1994 AW1 and 1991 VH (Pravec et al. 1997, 1998). Thus, it is clear that one cannot directly utilize the original data to construct the primary’s shape model. From the point of view of shape reconstruction, we should retrieve the short-period component from the observations in the very beginning. In the following,
we describe the method that detaches the short-period and long-period components.

By taking outside the deep minima from the long-period component, the short-period component can be obtained. Then, applying the Fourier fitting of the lightcurves to only short-period component, the rotational profile for the primary can be detached \cite{Mottola2003,Pravec2000}. The Fourier series is in the form of \cite{Harris1983,Pravec1996}

\[
R(t) = C_0 + \sum_{n=1}^{\infty} \left( C_n \cos \frac{2\pi n}{P}(t - t_0) + S_n \sin \frac{2\pi n}{P}(t - t_0) \right),
\]

where \(R\) is the magnitude computed at time \(t\), the period \(P = 3.5942 \pm 0.0002\) h, \(t_0\) is the epoch, \(C_0\), \(C_n\) and \(S_n\)
are the mean magnitude and the Fourier coefficients of the nth order, respectively. Subtracting the short-period component from the observation data by assuming the long-period added to the short-period linearly in irradiance, two kinds of components can be gained.

By subtracting short-period data, the long-period measurements show the information of eclipses/occultations which is not enough for the shape reconstruction of the secondary. Herein, we simply make use of the short-period data presented by the measurements that have been published already to precisely reconstruct the shape of the primary. We have already collected all optical data from 1996 to now, where there are 14 lightcurves of 1996 FG3 (see Table 1 in total [Mottola & Lahulla 2000, Pravec et al. 2000, 2004, Scheirich & Pravec, 2009, Wolters et al. 2011]. From the observation data of one to seven lightcurves, the best-fit fifth-order Fourier series separates the short-period component and the r.m.s residual is comparable to the observation errors. We can obtain the short-period data of the first seven lightcurves, where the first four lightcurves are adopted from Figure 1 of [Mottola & Lahulla 2000], while the data of the fifth to seventh lightcurves are from Figures 1 to 3 of [Pravec et al. 2000]. The short-period component of the first seven lightcurves has already obtained in the published papers. In the observation interval of the remaining lightcurves, no eclipsed or occultations occurred with an analysis of amplitude of the data. Note that Table 1 summarizes all measurements that we employed in the shape model, the data number in the table is simply referred to short-period data. Among them, seven lightcurves (labeled from No.1 to No.7) are in good quality to perform the fitting to model 3D shape of this asteroid, while the remaining data of each lightcurve from 8 to 14 are so short in the observation time, less than one rotation period of the primary, that we cannot get the short component from the total data, especially No.8 to No.12. The short-period component of lightcurves observed by [Wolters et al. 2011] (No.13 and No.14) can be obtained through Fourier fitting. However, we still use the data of No.13 and No.14 to perform additional investigation over the shape model, which is referred to cases A1 and A2, respectively. The detailed analysis will be given in the end of this section. In what follows we simply employ the data of the first seven lightcurves for exploring the physical properties of 1996 FG3, including the shape model inversion and the determination of the rotation period and the pole orientation for the primary.

We deal with the lightcurve data as the input format for deriving a shape model. All of data in the seven lightcurves are different, thus we first convert them to relative brightness. Using the observation epoch in JD, we calculate the ecliptic astrocentric cartesian coordinates of the Sun and Earth. Firstly we determine the rotation period of the primary by scanning in an interval of rotation period space. Secondly, the rotation period is fixed at the determined value and with free pole orientation parameters, the pole orientation and shape model are obtained. At last, in order to examine our results, we scan the $\chi^2$ value in the range of the orientation uncertainties.

Based on optical observations, the rotation period of 1996 FG3 is estimated to be $\sim 3.595 \pm 0.002$ h (Mottola & Lahulla 2000). Firstly, we confirm this spin period of primary using the methods of Kaasalainen et al. (2001 b) and [Durech et al. 2010]. In addition, we will find out a best-fit period on the basis of the published lightcurves, i.e., in search of a global minimum of $\chi^2$ in the fitting. In the parameter scanning process, six random pole directions are chosen. Using Levenberg-Marquardt [Press et al. 1992], for each pole the shape model and rotation period are simultaneously optimized to fit the observed lightcurves (Lowry et al. 2012). In this work, we choose a scanning range of period in [3.593, 3.597] h, based on the former outcomes (Mottola & Lahulla 2000, Pravec et al. 2004, 2006). Then, we carry out the calculations after iterating 50 steps for each run, and have a clearly minimum $\chi^2 = 0.005$ corresponding to the best-fitting rotation period of 3.5935 h for the primary which is consistent with that of Mottola & Lahulla (2000).

Furthermore, to determine the asteroid’s orientation, we then remain the rotation period as 3.5935 h, but let the orientation be free parameters. Herein, we adopt the initials of $\lambda = 242^\circ$ and $\beta = -84^\circ$ (Mottola & Lahulla 2000) to perform searching of orientation. For the simulation, we choose the convexity regularization weight to be 0.1, the laplace's coefficient, respectively. From this method, we are able to evaluate the orientation of 1996 FG3, the rotation period and a convex polyhedron shape model that consists of the coordinates of the vertices and the number of the facets of the polyhedron. After running many fittings, we finally obtain one of the best-fit solutions for the shape model of 1996 FG3, which is composed of 1022 vertices and 2040 facets (Table 1). Figure 2 shows the convex 3D shape from four view angles, north pole (top left), south pole (bottom left), equator (top right and bottom right), respectively. From Figure 2 in the left panels, we observe that north and south poles are both relatively flat within current resolution. The right panels show the equatorial views, where the equator of the asteroid seems to be most widest region and the south pole looks to be narrower than the north pole. And the left side is narrower than the right side shown in the bottom right panel in Figure 2. Thus from the shape model, Table 2 lists the initial conditions and the outcomes of the simulation for its shape. According to the calculation, the best-fit orientation of the target is determined to be $\lambda = 237.7^\circ$ and $\beta = -83.8^\circ$ with the $\chi^2 = 0.025$. Figure 3 shows the comparison results of the observation data in black dot and the modeled data in red solid line in panel (a) to (g). In Figure 3 the x-axis means the rotation phase and the y-axis represents the relative magnitude. From the figure, we conclude that the first seven lightcurves fit is good.
In order to ascertain whether the orientation is the most likely solution, we again scan the orientation in the range of its uncertainty for $\lambda = 242^\circ \pm 96^\circ$ and $\beta = -84^\circ \pm 14^\circ$ (Scheirich & Pravec 2009). Figure 4 shows the results, while the x-axis and y-axis represent the orientation $\lambda$ and $\beta$. The contour shows the value of $\chi^2$ by the colorbar index. In the figure, the yellow color corresponds to a small value of $\chi^2$ while the blue color is related to a larger value. The red cross in the figure represents the very orientation that we obtain from the shape model inversion programme. From the Figure, we can see that the value of $\chi^2 < 0.0251$ locates at the position of $\lambda = [231^\circ, 238^\circ]$ and $\beta = [-85^\circ, -81^\circ]$, which is shown in yellow region in Figure 4. The red cross just falls into the yellow region. However, the chi-squared values are very low over the scanning pole orientation space (Figure 4), indicating that the uncertainty in the position of the pole appears to be high as shown by Scheirich & Pravec (2009). As a result, we may come to the conclusion that the derived orientation is the best-fit solution in the range of the observation uncertainties.

Furthermore, we perform additional fitting and inverse the shape models with all of fourteen lightcurves (case A1) in Table 1 and eight lightcurves (case A2), which consist of the first seven and No.14 lightcurves. In both cases, we apply the Fourier fitting to deal with the observations given by Wolters et al. (2011). We repeat similar simulation process using fourteen lightcurves (case A1) and eight lightcurves (case A2), respectively. In case A1, the rotation period of the primary is determined to be 3.5943 h. Given the unaltered period and free pole orientation, we retrieve the shape model with the best-fit pole orientation at $\lambda = 238.8^\circ$ and $\beta = -87.6^\circ$. In case A2, we employ eight lightcurves that has been analyzed by Fourier fitting. In this case, the best-fit solution of the spin period and pole orientation is determined to be 3.5947 h, $\lambda = 234.5^\circ$ and $\beta = -82.0^\circ$, respectively. In comparison with three groups of solutions, we note that the outcomes of pole orientation and spin period do not vary dramatically. However, as the data in 2009 and 2011 appear to be sparse, simply covering the primary’s spin period much shorter than one rotational period, thus it is hard to precisely derive the short-period component using Fourier fitting with these data. Therefore, in this work we finally utilize the first seven lightcurves case to determine the shape model of 1996 FG3 (see Figure 2).

Recently, Arecibo and Goldstone completed the radar measurements for 1996 FG3 (Benner et al. 2012), where
both primary and the secondary are revealed. Compared with the radar images, we find that our derived shape model from optical observations bears a resemblance in some directions (Benner et al. 2012; Kaasalainen & Torppa 2001), which gives an indication of that the resultant shape of 1996 FG3 herein is reasonable. It is worth noting that the equatorial ridge of the primary revealed by the radar images is clearly seen in Figure 2. Moreover, the upper section in the bottom right panel seems to be consistent with the radar images.

4 SIMULATION

4.1 Observation Data

In this work, three sets of thermal-IR data of 1996 FG3 are utilized, summarized in Tables 3, 4, and 5. These three groups of published data are provided by Walsh et al. (2012) and Wolters et al. (2011), respectively. In addition, the observation geometry at three epochs are also described in Table 6, which are adopted to be input parameters in the calculation of thermophysical model.

Table 3. MIRSI Observations of 1996 FG3 on 1 May 2009 (Walsh et al. 2012)

| UT  | wavelength (µm) | Flux (10⁻¹⁴ Wm⁻²µm⁻¹) |
|-----|----------------|------------------------|
| 05:51 | 11.6           | 2.75 ± 0.07            |
| 05:53 | 11.6           | 2.87 ± 0.07            |
| 05:54 | 11.6           | 3.01 ± 0.07            |
| 05:59 | 8.7            | 3.40 ± 0.08            |
| 06:01 | 8.7            | 3.06 ± 0.08            |
| 06:10 | 18.4           | 1.59 ± 0.14            |
| 06:17 | 9.8            | 3.00 ± 0.13            |
| 06:20 | 9.8            | 3.27 ± 0.15            |
| 06:23 | 9.8            | 3.01 ± 0.14            |
| 06:25 | 11.6           | 2.75 ± 0.06            |
| 06:27 | 11.6           | 2.69 ± 0.07            |
| 06:30 | 8.7            | 2.98 ± 0.08            |
| 06:33 | 8.7            | 2.74 ± 0.09            |
| 06:36 | 8.7            | 3.02 ± 0.08            |
| 06:43 | 18.4           | 1.59 ± 0.14            |
| 06:48 | 11.6           | 2.44 ± 0.07            |
| 06:51 | 9.8            | 2.80 ± 0.15            |

4.2 Model Parameters

For a thermophysical model like ATPM, several physical parameters are required in the computation, such as the shape model, roughness, albedo, thermal inertia, thermal conduc-
tivity, thermal emissivity, heliocentric distance, geocentric distance, solar phase angle and so on. As the orbit of 1996 FG3 is accurately measured by optical observations, thus the heliocentric distance, geocentric distance and phase angle are not difficult to obtain.

Although the shape model of 1996 FG3 is derived from its lightcurves, we still do not know the actual physical size of 1996 FG3, because the shape model simply shows the relative dimensions of the asteroid. However, fortunately, the effective diameter $D_{\text{eff}}$, geometric albedo $p_v$, and absolute visual magnitude $H_v$ of an asteroid can be evaluated by the following equation (Fowler & Chilense 1992):

$$D_{\text{eff}} = \frac{1329 \times 10^{-H_v/5}}{\sqrt{p_v}} \, (\text{km}) ,$$

thus if two of the parameters are available, the third is easy to achieve.

However, the temperature distribution over the surface of an asteroid depends mainly on rotation state, thermal inertia, albedo and roughness, while the temperature distribution of sub-surface is greatly affected by thermal conductivity. Therefore, we will make use of surface temperature to derive a mean thermal inertia for 1999 FG3, and further to estimate a profile for thermal conductivity, so as to obtain a more accurate subsurface temperature distribution, then the regolith depth may be estimated more accurately. All required parameters are summarized in Table 7 except free parameters. Herein, we actually have three free parameters — thermal inertia, albedo or effective diameter and surface roughness, which are investigated in the fitting process.

### 4.3 Fitting Procedure

As 1996 FG3 is a binary system, and the rotation period of the secondary is 16.14 h, different from that of the primary, the flux of the secondary is modeled independently in the fitting procedure. The overall thermal flux predictions is a summation of that from both the primary and the secondary. Actually, the consideration of the flux of the secondary has no significant affect on the result, despite a very slight influence on the effective diameter. Thus, to simplify fitting process, we assume that the secondary shares an identical shape model with the primary.

On the other hand, the observations do not spatially resolve 1996 FG3. In this sense, the ATPM-derived diameter $D_{\text{eff}}$ is simply considered to be an effective diameter of a sphere with the combined cross-sectional area of two components. Thus, we suppose that the component diameters $D_1$ and $D_2$ are related to $D_{\text{eff}}$ via $D_1^2 + D_2^2 = D_{\text{eff}}^2$ (Walsh et al. 2012).

Surface roughness could be modeled by a fractional coverage of hemispherical craters, symbolized by $f_R$, while the remaining fraction, $1 - f_R$, represents a smooth flat surface on the asteroid. In this work, we adopt a low resolution hemispherical crater model that consists of 132 facets and 73 vertexes, following a similar treatment as shown in Rozitis & Green (2011). As well-known, the sunlight is fairly easier to be scattered on a rough surface than a smooth flat region, thus the roughness can decrease the effective Bond albedo. For the above-mentioned surface roughness model, the effective Bond albedo $A_{\text{eff}}$ of a rough surface can be related to the Bond albedo $A_B$ of a smooth flat surface and the roughness $f_R$ by (Walsh et al. 2012):

$$A_{\text{eff}} = f_R \frac{A_B}{2 - A_B} + (1 - f_R)A_B .$$

On the other hand, the effective Bond albedo $A_{\text{eff}}$ is related to geometric albedo $p_v$ by

### Table 5. VISIR observations of 1996 FG3 on 19 January 2011 (Wal ters et al. 2011)

| MJD-2455580 | wavelength (µm) | Flux $(10^{-15} \text{ Wm}^{-2} \mu\text{m}^{-1})$ |
|-------------|----------------|-----------------------------------|
| 0.14598     | 11.52          | 4.91 ± 0.17                       |
| 0.14538     | 11.52          | 4.63 ± 0.16                       |
| 0.15077     | 11.52          | 4.76 ± 0.16                       |
| 0.15473     | 8.70           | 4.96 ± 0.28                       |
| 0.15725     | 8.70           | 4.78 ± 0.26                       |
| 0.15966     | 8.70           | 5.41 ± 0.28                       |
| 0.16884     | 11.52          | 5.07 ± 0.19                       |
| 0.17124     | 11.52          | 4.89 ± 0.17                       |
| 0.17852     | 10.65          | 5.01 ± 0.25                       |
| 0.18108     | 10.65          | 5.92 ± 0.26                       |
| 0.18346     | 10.65          | 5.34 ± 0.25                       |
| 0.18930     | 11.52          | 5.07 ± 0.17                       |
| 0.19175     | 11.52          | 5.14 ± 0.17                       |
| 0.19467     | 12.47          | 4.48 ± 0.24                       |
| 0.19711     | 12.47          | 4.26 ± 0.23                       |
| 0.19949     | 12.47          | 4.70 ± 0.24                       |
| 0.20183     | 12.47          | 4.48 ± 0.24                       |
| 0.20421     | 12.47          | 4.68 ± 0.24                       |
| 0.20668     | 12.47          | 4.15 ± 0.23                       |
| 0.20962     | 11.52          | 4.43 ± 0.16                       |
| 0.21205     | 11.52          | 5.02 ± 0.17                       |
| 0.21575     | 8.70           | 5.55 ± 0.30                       |
| 0.21844     | 8.70           | 5.52 ± 0.28                       |
| 0.22179     | 8.70           | 5.30 ± 0.27                       |
| 0.22856     | 11.52          | 5.13 ± 0.17                       |
| 0.23097     | 11.52          | 4.91 ± 0.16                       |
| 0.23438     | 10.65          | 5.46 ± 0.26                       |
| 0.23701     | 10.65          | 5.43 ± 0.25                       |
| 0.23937     | 10.65          | 5.63 ± 0.25                       |
| 0.24282     | 11.52          | 5.13 ± 0.17                       |
| 0.24525     | 11.52          | 5.31 ± 0.17                       |
| 0.25203     | 12.47          | 4.74 ± 0.23                       |
| 0.25445     | 12.47          | 4.53 ± 0.23                       |
| 0.25683     | 12.47          | 4.41 ± 0.23                       |
Table 7. Assumed physical parameters used in ATPM.

| Property                        | Value   | References       |
|---------------------------------|---------|------------------|
| Number of vertices              | 1022    | this work        |
| Number of facets                | 2040    | this work        |
| Primary shape (a:b:c)           | 1.276:1.239:1 | this work       |
| Primary spin axis orientation   | $\lambda = 237.7^\circ$, $\beta = -83.8^\circ$ | this work       |
| Primary spin period             | 3.5935 h | this work        |
| Secondary spin period           | 16.14 h | (Scheirich & Pravec 2009) |
| $D_2/D_1$                       | $0.28^{+0.01}_{-0.02}$ | (Scheirich & Pravec 2009) |
| Absolute visual magnitude       | 17.833  | (Wolters et al. 2011) |
| Slope parameter                 | -0.041  | (Wolters et al. 2011) |
| Emissivity                      | 0.9     | assumption       |

Table 8. ATPM fitting results to the observations. (The combined effective diameters $D_{\text{eff}}$ are given in km)

| Roughness fraction | $f_R$ | $D_{\text{eff}}$ | $L^2$ | $D_{\text{eff}}$ | $L^2$ | $D_{\text{eff}}$ | $L^2$ | $D_{\text{eff}}$ | $L^2$ |
|--------------------|-------|------------------|------|------------------|------|------------------|------|------------------|------|
|                    |       |                  | 50   |                  | 100  |                  | 150  |                  | 200  |                  | 300  |
| 0.00               | 1.64  | 340.8            | 1.67 | 1101.0           | 1.68 | 2089.5           | 1.69 | 2926.4           | 1.70 | 3571.4           | 1.73  |
| 0.05               | 1.64  | 286.6            | 1.67 | 930.8            | 1.68 | 1900.0           | 1.69 | 2711.9           | 1.70 | 3401.4           | 1.73  |
| 0.10               | 1.64  | 267.6            | 1.67 | 777.5            | 1.68 | 1719.5           | 1.70 | 2505.0           | 1.71 | 3235.0           | 1.74  |
| 0.15               | 1.62  | 283.3            | 1.67 | 641.5            | 1.69 | 1548.3           | 1.70 | 2306.1           | 1.71 | 3072.3           | 1.73  |
| 0.20               | 1.63  | 332.9            | 1.67 | 522.7            | 1.69 | 1386.5           | 1.71 | 2115.5           | 1.71 | 2913.5           | 1.73  |
| 0.25               | 1.63  | 415.7            | 1.68 | 421.3            | 1.69 | 1234.2           | 1.71 | 1933.5           | 1.71 | 2758.5           | 1.74  |
| 0.30               | 1.63  | 530.7            | 1.68 | 334.7            | 1.69 | 1016.1           | 1.72 | 1760.4           | 1.72 | 2607.5           | 1.74  |
| 0.35               | 1.62  | 676.9            | 1.68 | 270.9            | 1.70 | 958.8            | 1.72 | 1596.4           | 1.72 | 2460.6           | 1.74  |
| 0.40               | 1.62  | 852.9            | 1.68 | 221.7            | 1.70 | 835.9            | 1.73 | 1422.0           | 1.72 | 2317.7           | 1.74  |
| 0.45               | 1.61  | 1057.7           | 1.68 | 190.0            | 1.70 | 733.0            | 1.73 | 1297.3           | 1.72 | 2179.0           | 1.74  |
| 0.50               | 1.61  | 1289.9           | 1.67 | 175.4            | 1.70 | 620.1            | 1.74 | 1162.6           | 1.73 | 2044.5           | 1.75  |
| 0.55               | 1.60  | 1548.1           | 1.68 | 177.9            | 1.70 | 527.4            | 1.74 | 1038.2           | 1.73 | 1914.3           | 1.75  |
| 0.60               | 1.59  | 1830.9           | 1.67 | 197.4            | 1.70 | 444.9            | 1.74 | 924.3            | 1.73 | 1788.4           | 1.75  |
| 0.65               | 1.59  | 2136.8           | 1.67 | 233.5            | 1.70 | 372.5            | 1.75 | 821.3            | 1.73 | 1666.9           | 1.75  |
| 0.70               | 1.58  | 2464.5           | 1.67 | 286.1            | 1.70 | 310.5            | 1.75 | 729.2            | 1.73 | 1549.8           | 1.76  |
| 0.75               | 1.57  | 2812.3           | 1.67 | 354.9            | 1.70 | 258.7            | 1.75 | 648.4            | 1.74 | 1437.3           | 1.76  |
| 0.80               | 1.56  | 3178.6           | 1.67 | 439.5            | 1.70 | 217.2            | 1.76 | 579.0            | 1.74 | 1329.2           | 1.76  |
| 0.85               | 1.55  | 3562.6           | 1.66 | 539.7            | 1.70 | 185.9            | 1.76 | 521.2            | 1.74 | 1225.7           | 1.76  |
| 0.90               | 1.55  | 3962.2           | 1.66 | 655.1            | 1.70 | 164.9            | 1.76 | 475.3            | 1.74 | 1162.8           | 1.76  |
| 0.95               | 1.54  | 4376.0           | 1.66 | 785.3            | 1.70 | 154.0            | 1.76 | 441.2            | 1.74 | 1032.6           | 1.76  |
| 1.00               | 1.53  | 4802.9           | 1.65 | 929.8            | 1.70 | 153.3            | 1.77 | 419.3            | 1.75 | 943.1            | 1.77  |

\[ A_{\text{eff}} = p \phi_{ph} , \]  
\[ q_{ph} = 0.290 + 0.684G , \]
\[ FCF = \frac{1 - A_{B,\text{now}}}{1 - A_{B,\text{initial}}} , \]

where $q_{ph}$ is a phase integral that can be approximated by (Bowell et al. 1989),
\[ q_{ph} = 0.290 + 0.684G , \]
where $G$ is the slope parameter in the $H, G$ magnitude system of Bowell et al. (1989), we chose $H = 17.833 \pm 0.024$, $G = -0.041 \pm 0.005$ (Wolters et al. 2011) in our fitting process. Thus each surface roughness and effective diameter leads to a unique $A_{\text{eff}}$ and $A_B$.

In order to simplify our modeling process, a set of thermal inertia are selected in the range $0 \sim 500$ Jm$^{-2}$s$^{-0.5}$K$^{-1}$. And for each thermal inertia case, a series of surface roughness and effective diameter are calculated to examine which may act as best-fit parameters with respect to the observations.

As ATPM requires a Bond albedo $A_B$ for each facet element to simulate temperature distribution, thus an $A_B = 0.01$ is herein assumed to be initial for two components of 1996 FG3. For each thermal inertia $\Gamma$, effective diameter $D_{\text{eff}}$ and surface roughness $f_R$ case, a flux correction factor $FCF$ is defined as (Wolters et al. 2011)
The heavy line is a cubic spline interpolation curve for each lowest
Derived properties of 1996 FG3 from ATPM.
roughness fraction and effective diameter according to
Figure 5.

The dashed curve represents a roughness fraction \( f_R \) in the range of 0.0 \( \sim \) 1.0.
The heavy line is a cubic spline interpolation curve for each lowest
\( L^2 \) derived from each free parameter.

5.1 Temperature Distribution

Figure 5 shows the equatorial temperature distribution of 1996 FG3 at its aphelion and perihelion respectively. The maximum temperature does not appear at the solar point, but delays about 24°, and the minimum temperature occurs just a little after the local sunrise, delaying about 18°. Such delay effect between absorption and emission is actually caused by the non-zero thermal inertia and the finite rotation speed of the asteroid. On the other hand, according to Figure 5, the equatorial temperature of 1996 FG3 may range from 180 to 480 K over a whole orbit period.

Figure 4 shows the global surface temperature distribution of 1996 FG3 at its aphelion (left) and perihelion (right) respectively. In this figure, z-axis represents the asteroid’s spin axis, and x-axis points to the Sun in the framework of an asteroid center body-fixed coordinate system. The profile of temperature in Figure 4 is shown by the index of color bar, and the red region represents the facets are sunlit, while the blue facets are referred to relatively low temperature.

Table 9. Derived properties of 1996 FG3 from ATPM.

| Property            | Result          |
|---------------------|-----------------|
| Thermal inertia \( \Gamma \) (J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\)) | 80 \( \pm \) 40 |
| Roughness fraction \( f_R \)          | 0.8 \( \pm \) 0.2 |
| Geometric albedo \( p_v \)          | 0.045 \( \pm \) 0.002 |
| Effective diameter \( D_{\text{eff}} \) (km) | 1.69 \( \pm \) 0.03 |
| Primary diameter \( D_1 \) (km)    | 1.63 \( \pm \) 0.03 |
| Secondary diameter \( D_2 \) (km)   | 0.45 \( \pm \) 0.03 |

In the following section, we will then utilize the above derived parameters to evaluate the surface thermal environment of 1996 FG3 at its aphelion and perihelion respectively.

5 SURFACE THERMAL ENVIRONMENT

5.2 Regolith

As mentioned previously, 1996 FG3 is chosen to be a backup target for MarcoPolo-R sample return mission. Hence, we still show great interest in the surface feature of the asteroid whether there exists a regolith layer on its surface. Apparently, thermal inertia is associated with the surface properties, where it will be helpful to infer the presence or absence of loose material on the surface. As known to all, fine dust has a very low thermal inertia about 30 J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\), lunar regolith owns a relatively low value about 50 J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\), a sandy regolith like Eros’ soil bears a value of 100–200 J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\), but coarse sand occupies a higher thermal inertia profile \( \sim 400 \) J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\) (e.g., Itokawa’s Muses-Sea Regio). In comparison with the above materials, bare rock has an extremely higher thermal inertia more than 2500 J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\) \( \text{(Delbo et al. 2007).} \)

In this work, the thermal inertia of 1996 FG3 is estimated to be 80 \( \pm \) 40 J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\). Consequently, it is quite natural for one to suppose that the surface of 1996 FG3 may be covered by loose materials, perhaps a mixture of dust, fragmentary rocky debris and sand. In other word, there may exist a regolith layer on the surface of 1996 FG3, according to the above derived thermal inertia.

Theoretically, the so-called "skin depth":

\[
L_s = \sqrt{\frac{\kappa}{\rho c \omega}}
\]

is usually used to characterize the grain size of regolith. According to the definition of thermal inertia \( \Gamma = \sqrt{\rho c \kappa} \). The profiles of mass density \( \rho \), thermal conductivity \( \kappa \), and specific heat capacity \( c \) may be estimated from the above derived thermal inertia. Since the thermal conductivity \( \kappa \) depends on particle size and temperature much more than \( \rho \) and \( c \), we attempt to assume a constant value for \( \rho \) and \( c \), and then estimate \( \kappa \) from the above derived thermal inertia. Next, the estimation of skin depth will be easily acquired. \( \text{(Scheirich & Pravec 2003) has derived the mass density to be 1.4 \( \pm \) 0.6 g cm}^{-3} \). Since the above derived value \( \Gamma = 80 \pm 40 \) J m\(^{-2}\) s\(^{-0.5}\) K\(^{-1}\) is similar to that of the Moon despite a little higher, we assume the specific heat capacity of 1996 FG3 is similar to that of the Moon, about...
Figure 6. Equatorial temperature distribution of 1996 FG3 at aphelion and perihelion, respectively. Maximum temperature at 24°, minimum temperature at −72°. (0° is the sub-solar point.)

Figure 7. Global surface temperature distribution obtained from ATPM at the aphelion and perihelion, respectively. The color bar indicates the range of temperature, where red for high temperature and blue for low temperature.
1000 Jkg\(^{-1}\)K\(^{-1}\). Then the thermal conductivity \(\kappa\) is estimated to be 0.001 \(\sim\) 0.01 Jkg\(^{-1}\)K\(^{-1}\) and \(l_s\) is 1.3 \(\sim\) 3.9 mm. Such small \(\kappa\) and \(l_s\) obviously support the possible existence of loose material or regolith over the surface of 1996 FG3. However, the depth of the regolith layer, covered on the asteroid's surface, attracts our great attention.

We carried out simulations to explore the regolith depth versus temperature distribution of sub-surface for \(\Gamma = 40, 80\) and \(120\) Jm\(^{-2}\)s\(^{-0.5}\)K\(^{-1}\), respectively (see Figure 8). The left panels show the results are obtained when the asteroid moves at aphelion, while the right panels exhibit those at perihelion. In each panel, two profiles, which are respectively, plotted by solid line (local midday) and dashed line (local midnight), show that the sub-surface temperature changes with the depth (the distance from the surface). In these panels, the temperature goes down as the depth increases at local noon, while it goes up as the depth increases at local midnight until a certain depth, where two curves are overlapped. This phenomenon results from the internal boundary equation \([1]\). The figure shows the temperature distribution of the very loose regolith layer, the thermal conductivity of which may be in the range of 0.001 \(\sim\) 0.01 Jkg\(^{-1}\)K\(^{-1}\). And the minimum depth of this layer may be estimated from Figure 8. Herein the regolith depth of the very surface of 1996 FG3 is reckoned to be 5 \(\sim\) 20 mm. This minimum value of regolith depth may be considered as a reference for the design of a spacecraft if a lander is equipped. On the other hand, the existence of regolith over the surface of the primary of 1996 FG3 actually does good to a sample return mission.

6 DISCUSSION AND CONCLUSION

In this work, we have derived a new 3D convex shape model of the primary of 1996 FG3 from the published lightcurves, where the best-fit orientation of its spin axis is determined
to be $\lambda = 237.7^\circ$ and $\beta = -83.8^\circ$, with a rotation period of $\sim 3.5935$ h. On the basis of the numerical codes independently developed according to thermophysical model, we apply the shape model and the required input physical parameters to fit three sets of mid-infrared measurements for 1996 FG3. Herein we summarize the major physical parameters to fit three sets of mid-infrared measurements for 1996 FG3. Depending on the adopted roughness model in the ATPM, we perform the computation using the combination data (Tajika et al. 2005, 2011, 2012). Hence, this enables us to conclude that the fitting process is correct and the derived results are reliable.

According to the ATPM fitting results shown in Table 2, the large roughness fraction $f_R = 0.8 \pm 0.2$ for 1996 FG3 may suggest a rough surface on the asteroid. However, the asteroid’s mean surface thermal inertia is estimated to be a relative low value. Then the question arises – why this asteroid bears such a low thermal inertia with a very rough surface. As the adopted roughness model in the ATPM is assumed to be an irregularity degree of a surface at scales smaller than the global shape model resolution (like a facet area) but larger than the thermal skin depth. Therefore, 1996 FG3 would be likely to have a rough surface, which may or may not include craters of any size, and a porous or dusty material. The recent work of Perna et al. (2013) suggested the surface of 1996 FG3 may be a compact one, with the existence of regions showing different roughness, similar to that of Itokawa. Hence, there would be possible for an asteroid to possess a large roughness fraction and low thermal inertia.

However, the NEA binaries may have a high averaged thermal inertia of $\Gamma \approx 480 \pm 70$ Jm$^{-2}$s$^{-0.5}$K$^{-1}$ (Delbo et al. 2011), indicating that high thermal inertia could be supportive to the binary formation scenario due to YORP mechanism. In this work, we have derived thermal inertia $\Gamma = 80 \pm 40$ Jm$^{-2}$s$^{-0.5}$K$^{-1}$ for 1996 FG3, and it appears below their estimation. Nevertheless, it is still likely for a rubble-pile asteroid to have a low thermal inertia, thereby remaining a rough surface during a long dynamical evolution due to space-weathering and regolith migration. In this sense, the binary 1996 FG3 may also be produced via the YORP rotation acceleration effect at a very earlier time, but retain a roughness surface from then, resulting in the distribution of a great many meter-size (or even smaller) craters on the surface. Thus, these tiny craters might be covered or surrounded by loose materials, making it appear a low thermal inertia.

Delbo et al. (2007) showed that the average thermal inertia for NEAs may be $\Gamma = 200 \pm 40$ Jm$^{-2}$s$^{-0.5}$K$^{-1}$. Figure 14 exhibits the variation of mean thermal inertia with the size of asteroids from the observations. From this figure, we observe that the value of thermal inertia for 1996 FG3 given in this work (labeled in red) deviates a little from the prediction profile. In addition, our outcome for the binary system is a bit lower than that of Wolters et al. (2011). This results from that we perform the combination fitting with
additional thermal-IR observations (Tables 3 and 4), which may provide new insight for the thermal study of binary asteroids.

In conclusion, the surface of 1996 FG3’s primary may be a very rough surface, on which loose materials such as fine dust, fragmentary rocky debris, sands or most likely a stuff of their mixture are covered, composing a kind of regolith. The depth of the possible regolith layer is evaluated to be approximately 5 ~ 20 mm. Such implication may provide substantial information for engineering of the sample return mission, for example, a selection of landing area. However, we should place special emphasis on that this estimation is simply a roughly minimum value of the regolith layer over the very surface of the asteroid rather than a sort of megaregolith below the layer. Since the thermal conductivity $\kappa$ of the megaregolith has a complicated relationship with the depth below the surface (Haack et al. 1990), thereby we cannot simulate the temperature distribution accurately from a one-dimension thermophysical model. On the other hand, the formation mechanism for 1996 FG3 is still a mystery, which the YORP acceleration mechanism may play a role in producing its shape and orbital configuration (Walsh et al. 2003). In short, the investigations by future space missions will throw new light on the formation scenario for this asteroid.

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REFERENCES

Barucci, M. A., Cheng, A. F., Michel, P., et al. 2012, Experimental Astronomy, 33, 645
Benner, L.A., et al. 2012, Asteroids, Comets, Meteors, 6403
Binzel, R. P., Harris, A. W., Bus, S. J., & Burbine, T. H. 2001, Icarus, 151, 139
Binzel, R. P., Polishook, D., DeMeo, F. E., Emery, J. P., & Rivkin, A. S. 2012, Lunar and Planetary Institute Science Conference Abstracts, 43, 2222
Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peltoniemi, J. & Harris, A.W. 1989, Application of photometric models to asteroids. In Asteroids II, pp. 524-556
Christou, A. A., 2003, Planet. Space Sci., 51, 221
Delbo, M., & Harris, A.W., 2002, Meteoritics & Planetary Science, 37, 1929-1936
Delbo, M., Oro, A., Harris, A.W., Mottola, S., & Muller, M., 2007, Icarus, 190, 236-249
Delbo, M., Walsh, K., Mueller, M., Harris, A.W., & Howell, E.S., 2011, Icarus, 212, 138
de León, J., Moth-Hinze, T., Licandro, J., Pinilla-Alonso, N., & Campins, H., 2011, A&A, 530, L12
de León, J., Lorenzi, V., Ali-Lagoa, V., et al. 2013, A&A, 556, A33
Durech, J., Sidorin, V., & Kaasalainen, M., 2010, A&A, 513, A46
Fowler, J.W., & Chillemi, J.R., 1992, IRAS asteroids data processing. In The IRAS Minor Planet Survey, pp.17-43

© 2002 RAS, MNRAS 000, 1–15
Haack, H., Rasmussen, K. L., Warren, P. H., 1990, JGR, 95, 5111
Harris, A.W. et al., 1989, Icarus, 77, 171
Harris, A.W., 1998, Icarus, 131, 291-301
Kaasalainen M. & Torppa J., 2001, Icarus, 153, 24
Kaasalainen M., Torppa, J., & Muinonen, K., 2001, Icarus, 153, 37
Lagerros, J.S.V., 1996, A&A. 310, 1011-1020
Lowry, S. et al., 2012, A&A, 548, A12
Mottola, S., & Lahulla, F., 2000, Icarus, 146, 556
Müller, T.G., Sekiguchi, T., Kaasalainen, M., Abe, M., & Hasegawa, S., 2005, A&A, 443, 347
Müller, T.G., Durech, J., Hasegawa, S., et al., 2011, A&A, 525, A145
Müller, T.G., O’Rourke, L., Barucci, A.M., et al., 2012, A&A, 548, A36
Mueller, M., Delbo, M. Hora, J., et al., 2011, AJ, 141, 109
Perna, D., Dotto, E.A.B., Fornasier, S., et al., 2013, A&A, 555, A62
Perozzi, E., Rossi, A., & Valsecchi, G. B., 2001, Planet. Space Sci., 49, 3
Pravec, P., Sarounova, L., Wolf, M., 1996, Icarus, 124, 471
Pravec, P., & Hahn, G., 1997, Icarus, 127, 431
Pravec, P., Wolf, M., Sarounova, L., 1998, Icarus, 133, 79
Pravec, P., Sarounova, L., Rabinowitz, D.L., et al., 2000, Icarus, 146, 190
Pravec, P., Scheirich, P., Kusnirak, P., et al., 2006, Icarus, 181, 63
Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. 1992, Numerical Recipes in C, 2nd ed., Cambridge: University Press
Rivkin, A. S., Howell, E. S., Vervack, R. J., et al. 2013, Icarus, 223, 493
Rozitis, B., & Green, S.F., 2011, MNRAS, 415, 2042
Rozitis, B., & Green, S.F., 2012, MNRAS, 423, 367
Scheirich, P., & Pravec, P., 2009, Icarus, 200, 531
Spencer, J.R., Lebofsky, L.A., & Sykes, M.V., 1989, Icarus, 78, 337
Walsh, K.J., Delbo, M., Mueller, M., Binzel, R.P., & DeMeo, F.E., 2012, ApJ, 748, 104
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