A new non-convex model of the binary asteroid (809) Lundia obtained with the SAGE modelling technique

P. Bartczak1*, A. Kryszczyńska1, G. Dudziński1, M. Polińska1, F. Colas2, F. Vachier2, A. Marciniak1, J. Pollock3, G. Apostolovska4, T. Santana-Ros1, R. Hirsch1, W. Dimitrow1, M. Murawiecka7, P. Wietrzycka1, and J. Nadolny5,6

1 Astronomical Observatory Institute, Faculty of Physics, Adam Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland.  
2 IMCCE, Observatoire de Paris, 61, Avenue Denfert-Rochereau, 75014 Paris, France.  
3 Physics and Astronomy Department, Appalachian State University, Boone, NC 28608, USA.  
4 Institute of Physics, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Arhitektonica 3, 1000 Skopje, Macedonia.  
5 Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain.  
6 Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain.  
7 NaXys, Department of Mathematics, University of Namur, 8 Rempart de la Vierge, 5000 Namur, Belgium.

ABSTRACT

We present a new non-convex model of the binary asteroid (809) Lundia. A SAGE (Shaping Asteroids with Genetic Evolution) method using disc-integrated photometry only was used for deriving physical parameters of this binary system. The model of (809) Lundia improves former system’s pole solution and gives the ecliptic co-ordinates of the orbit pole – $\lambda = 122^\circ$, $\beta = 22^\circ$, $\sigma = \pm 5^\circ$ – and the orbital period of $T = 15.41574 \pm 0.00001$ h. For scaling our results we used effective diameter of $D_{\text{eff}} = 9.6 \pm 1.1$ km obtained from Spitzer observations. The non-convex shape description of the components permitted a refined calculation of the components’ volumes, leading to a density estimation of $\rho = 2.50 \pm 0.20$ g/cm$^3$ and macroporosity of 13-23%. The intermediate-scale features of the model may also offer new clues on the components’ origin and evolution.

Key words: methods: numerical – techniques: photometric.

1 INTRODUCTION

(809) Lundia was classified as a V-type asteroid in the Flora dynamical family (Florczak et al. 2002). The discovery of its binary nature in September 2005 was based on photometric observations carried out at Borowiec observatory (Kryszczyńska et al. 2005). The first modelling of the Lundia synchronous binary system was based on 23 lightcurves obtained at Borowiec and Pic du Midi Observatories during two oppositions in 2005/2006 and 2006/2007. The two methods of modelling - modified Roche ellipsoids and kinematic - gave similar parameters of the system (Kryszczyńska et al. 2009). The poles of the orbit in the ecliptic coordinates found were: longitude $118 \pm 2^\circ$, and latitude $28 \pm 2^\circ$ in the modified Roche model and $120 \pm 2^\circ$, $18 \pm 2^\circ$ respectively in the kinematic model (Kryszczyńska et al. 2009). The orbital period obtained from the lightcurve analysis as well as from modelling was $15.418 \pm 0.001$ h. The obtained bulk density of both components was $1.64$ or $1.71$ g/cm$^3$. The comparison with HED meteorites gave very high macroporosity of 42 – 49%. Spectroscopic observations of the (809) Lundia system were performed using NASA Infrared Telescope Facility and SpeX spectrograph in 2005, 2007 and 2010. One of these spectra, observed during total eclipse of the components allowed to investigate homogeneity/heterogeneity of both bodies. Detailed analysis of all spectra confirmed similar mineralogy of both components. By applying different mineralogical models a composition similar to the one of howardite-diogenite meteorites was found (Birlan et al. 2014).

Finding bulk density is the main goal of modelling asteroids’ physical properties, as it gives insights into their internal structure and composition. Determining the latter based on spectroscopy or albedo probing only the surface of the body leads to strongly biased bulk densities, but one can use that data to find meteorite analogs for further comparison. Besides density, macroporosity is another valuable information putting constrains on e.g. evolution or collisional
lifetime (Britt et al. 2002). Macroporosity can be found by comparing meteorite analogs’ density and porosity with the density derived from independent method and data like photometry based shape modelling.

Density estimation relies on the estimations of the mass and volume. As summarized by Carry (2012), mass can be estimated using several methods: orbit deflection during close encounters, planetary ephemeris, spacecraft tracking or studying orbit of a satellite. Although spacecraft tracing technique is the most precise, it is limited to small number of space missions’ targets. Very good results (of 10-15% accuracy) can be achieved with binary asteroids, where one can derive total mass of the system from Kepler’s 3rd law once the satellite’s orbit is known.

To know the asteroid’s volume, detailed shape model and its size are needed. Among the methods of size estimation, about 85% of asteroids’ sizes were obtained with thermal modeling. Majority of those estimates have relative uncertainty of about 5%, however there are some indications of these values being underestimated (Carry 2012). Methods capable of deriving convex shapes only (e.g. spheres, tri-axial ellipsoids or Roche ellipsoids) put lower constraints on the density, as introducing concavities will increase density of the body with the same equivalent sphere diameter and period. In-situ observations revealed concave nature of asteroids in general, which makes non-convex methods more adequate and accurate.

According to a list of binaries’ parameters 1 described first in (Pravec & Harris 2007), there are only 12 double synchronous asteroids discovered so far. Synchronous binary asteroids with circular orbits are special cases of binary systems where rotational periods of both components are equal to orbital one. Additionally, angular momenta of components, orbit and resulting system’s one are parallel. This reduces the amount of free parameters of the model and allow for detailed shape modelling leading to more accurate volume estimates.

In this paper we present a new non-convex model of the (809) Lundia system using SAGE (Shaping Asteroids with Genetic Evolution) method using disc-integrated photometry only, described by Bartczak et al. (2014). This method was successfully applied to model the binary asteroid (90) Antiope.

2 OBSERVATIONS

We continued observations of (809) Lundia system in 2007, 2008, 2009/2010, 2011, and 2012 oppositions at Borowiec, Pic du Midi, PROMPT, South African Astronomical Observatory, and Bulgarian National Observatory Rozhen. As predicted the well visible eclipses/occultation events were observed only in 2011. Signs of partial eclipses/occultation are visible in the lightcurves from 2012 opposition. In Fig. 1 we show positions of the Earth in the reference frame of the asteroid. Blue dots represent observations with eclipse/occultation events and green without events. Open circles represent future observing geometries and show that in 2018 only there will be a chance to observe eclipses/occultation events.

Observations at Borowiec observatory were carried out with 0.4m Newton telescope equipped with the KAF402ME CCD camera and clear filter. The details of the Borowiec system were described by Michałowski et al. (2004). Observations from SAAO were carried out at 0.76m reflector equipped with the University of Cape Town (UCT) CCD camera and R filter.

All CCD frames from Borowiec and SAAO were reduced for bias, dark current, and flatfield using CCLR STARLINK package. The aperture photometry was performed to measure the instrumental brightness of the asteroid and the comparison and check stars. Lightcurves observed at Pic du Midi in 2009 were obtained using 1.05m Cassegrain telescope equipped with THX 7863 CCD camera and L filter. Lightcurves from 2011 were taken using Andor iKon-L CCD camera and L filter. A standard reduction was performed using Audela software (http://www.audela.org) whose photometry analysis was developed at IMCCE in Paris. Observations at the Bulgarian National Observatory at Rozhen were carried out with the 0.5/0.7m Schmidt telescope and KAF1602E CCD camera and R filter. For the data reduction and aperture photometry the IDL software was used. Three lightcurves were obtained by PROMPT 4, a 0.41m Ritchey-Chrétien telescope located in Cerro Tololo Inter-American Observatory in Chile, equipped with Alta U47+ camera. The aspect data of Lundia are listed in Table 1.

The obtained composite lightcurves are presented in Figs. 2-6. Lightcurves are composed with the synodic period of $15.418\pm0.001\ h$. For good comparison between lightcurves the scale on each graph is the same. In Fig 2, we present a lightcurve from NAO Rozhen in comparison with already published lightcurves from Pic du Midi. Despite the time span between the lightcurves is as much as four months the internal fit is very good and it confirms the derived synodic period. Currently, our dataset consists of 41 individual lightcurves obtained during 6 oppositions and covering

\footnote{1 http://www.asu.cas.cz/ asteroid/binastdata.htm}
The modelling process uses genetic algorithm to arrive at global minimum. The modelling starts with the two spheres, random spin axis orientation and approximate rotational period. In every step a random changes to the shapes, period, spin axis orientation, separation and size ratio are applied creating a random population (generation) of systems. Each body of the system is a physical model assuming homogeneous distribution of mass; the axes of largest inertia of the bodies are aligned with spin axis of the whole system. Then, for every model of the system in the population a synthetic lightcurves are calculated and compared with observations using $\chi^2$ test. The model with smallest $\chi^2$ is chosen as the seed for the next population and the whole process repeats until $\chi^2$ value no longer changes from population to population. In order to assure the modelling process not to fall into local minimum a weighting process is applied in every step. The lightcurve with largest $\chi^2$ is given the largest weight to steer the process towards the global minimum; the weights change in every step.

Additionally, the whole modelling process is run multiple times creating a family of solutions. This is a standard procedure in genetic evolution algorithms to ensure the result being in global, rather than local, minimum. The path leading to a model in each run is different, but the models should be alike in the end. If the models differ significantly, it indicates that not enough observational data has been supplied for the modelling.

### Table 1. Aspect data. Columns give dates of observations with respect to the middle of the lightcurve, asteroid’s distances to the Sun ($r$) and Earth ($\Delta$) in AU, phase angle ($\alpha$), ecliptic longitude ($\lambda$) and latitude ($\beta$) for J2000.0 and the observatory.

| Date (UT) | $r$ (AU) | $\Delta$ (AU) | Phase angle ($\alpha$) | $\lambda$ (J2000) | $\beta$ (°) | Observatory |
|-----------|---------|--------------|----------------------|-----------------|----------|-------------|
| 2007 Apr 04.91 | 2.7186 | 1.9977 | 17.29 | 159.95 | 3.73 | NAO Rozhen |
| 2008 May 07.32 | 2.1530 | 1.5361 | 25.38 | 292.88 | 9.27 | PROMPT |
| 2008 May 08.29 | 2.1509 | 1.5242 | 25.25 | 293.05 | 9.31 | PROMPT |
| 2008 May 09.30 | 2.1487 | 1.5118 | 25.11 | 293.22 | 9.36 | PROMPT |
| 2008 Jun 10.92 | 2.0776 | 1.1682 | 16.68 | 294.94 | 10.59 | SAAO |
| 2009 Nov 20.10 | 2.4282 | 1.9806 | 23.26 | 133.39 | -6.17 | Pic du Midi |
| 2009 Nov 25.14 | 2.4336 | 1.9276 | 22.57 | 133.93 | -6.23 | Pic du Midi |
| 2011 Apr 07.07 | 2.5479 | 1.6394 | 11.81 | 226.89 | 9.72 | Pic du Midi |
| 2011 Apr 08.10 | 2.5462 | 1.6310 | 11.86 | 226.71 | 9.79 | Pic du Midi |
| 2011 Apr 09.06 | 2.5446 | 1.6334 | 11.09 | 226.55 | 9.85 | Pic du Midi |
| 2011 Apr 11.10 | 2.5414 | 1.6080 | 10.34 | 226.17 | 9.97 | Pic du Midi |
| 2011 Apr 12.08 | 2.5309 | 1.6009 | 9.98 | 225.98 | 10.03 | Pic du Midi |
| 2012 Oct 09.04 | 1.9847 | 1.2466 | 24.71 | 71.60 | -10.87 | Borowiec |
| 2012 Oct 18.05 | 2.0017 | 1.1901 | 21.59 | 71.60 | -11.69 | Borowiec |
| 2012 Oct 18.02 | 2.0035 | 1.1864 | 21.21 | 71.55 | -11.77 | Borowiec |
| 2012 Oct 20.07 | 2.0056 | 1.1787 | 20.80 | 71.49 | -11.86 | Borowiec |
| 2012 Nov 11.05 | 2.0495 | 1.1012 | 10.87 | 67.95 | -13.31 | Borowiec |
| 2012 Nov 26.03 | 2.0810 | 1.1086 | 6.36 | 63.95 | -13.50 | Borowiec |

The Lundia shape model projections can be seen in Fig. 4. Synthetic lightcurves generated by the model fit the observed ones very well (Fig. 4). Mutual eclipse events are perfectly timed and the lightcurves’ shape is reproduced on general and detail levels. The uncertainty of photometry was different from observed ones very well (Fig. 4).
Table 2. Details of the lightcurves used for our modelling of (809) Lundia. The table columns describe the observations time range, the number of observing nights, the phase angle range, the ecliptic longitudes and latitudes of the asteroid around the opposition dates, the observed eclipsing amplitudes and the references. The value of '0' for the eclipsing amplitudes means that no eclipses were observed for these apparitions (i.e. 2006/2007, 2008 and 2009).

| Time range      | $N_{\text{lc}}$ | $\alpha$ (°) | $\lambda$ (°) | $\beta$ (°) | Eclipsing amplitude (mag) | Reference                  |
|-----------------|-----------------|---------------|---------------|-------------|---------------------------|-----------------------------|
| Sep 2005 – Jan 2006 | 19              | 7.3 – 25.9    | 45            | -11         | 0.75 – 0.30               | Kryszczynska et al. (2005)  |
| Dec 2006 – Apr 2007 | 4+1             | 17.3 – 21.4   | 168           | 2           | 0                         | Kryszczynska et al. (2005) and this paper |
| May 2008 – Jun 2008 | 4               | 16.7 – 25.3   | 294           | 10          | 0                         | this paper                 |
| Nov 2009        | 2               | 22.6 – 23.3   | 133           | -6          | 0                         | this paper                 |
| Apr 2011        | 5               | 10.0 – 11.8   | 226           | 10          | 0.58                      | this paper                 |
| Oct 2012 – Nov 2012 | 6               | 6.4 – 24.7    | 68            | -12         | 0 – 0.15                  | this paper                 |

Figure 2. Composite lightcurves of 809 Lundia from 2006/2007 opposition (top) with corresponding view of the system from Earth (bottom).

Figure 3. Composite lightcurves of 809 Lundia from 2008 opposition (top) with corresponding view of the system from Earth (bottom).
not reported by the observers and therefore it is assumed to be 0.02 mag.

Using Spitzer Space telescope Marchis et al. (2012) calculated effective diameter of Lundia $D_{eff} = 9.6$ km with 3σ uncertainty of 1.1 km. Combining this result with inhomogeneous Roche ellipsoids model by Descamps (2010) they obtained equivalent sphere diameters for the primary and secondary components $D_p = 7.2 \pm 1.4$ km and $D_s = 6.4 \pm 1.3$ km, with system separation $d = 14.6$ km and average bulk density of the system $\rho = 1.77$ g/cm$^3$.

Applying said effective diameter we scaled the new non-convex Lundia model by assuming the same volume of the system. Mass was determined from the orbital period $P$ and system separation $d$ using Kepler’s third law.

The parameters of non-convex model of Lundia system are:

- system’s spin axis ecliptic coordinates:
  \[ \lambda = 122.5 \pm 5^\circ, \quad \beta = 22 \pm 5^\circ \]
- sidereal period: $P = 15.41574 \pm 10^{-5}$ h
- primary equivalent sphere diameter: $D_p = 8.1 \pm 0.9$ km
- secondary equivalent sphere diameter: $D_s = 7.1 \pm 0.8$ km
- $D_s/D_p = 0.87$
- system separation: $d = 18.2 \pm 0.8$ km
- total mass: $(1.157 \pm 0.4) \times 10^{15}$ kg
- bulk density: $\rho = 2.5 \pm 0.2$ g/cm$^3$
- macroporosity: 19-23%

Spectroscopic observations’ analysis (Birlan et al. 2014) indicates similar mineralogical composition as howardite-diogenite meteorites. The obtained density of 2.5 g/cm$^3$
Figure 6. Composite lightcurve of 809 Lundia from 2012 opposition (top) with corresponding view of the system from Earth (bottom).

is much higher than determined before, and this value in comparison with the density of HED meteorites of 2.86 to 3.26 g/cm$^3$ reported by Britt & Consolmagno (2003) and McCausland & Flemming (2006) infers the macroporosity of (809) Lundia of only 13-23%, rather than 40-50% as reported by Marchis et al. (2012).

5 CONCLUSIONS

The obtained non-convex model of (809) Lundia perfectly reproduces the obtained set of photometric lightcurves. By scaling volume of the system components we found density 50% higher than the one calculated in the previous studies and macroporosity of about 60% smaller than before Kryszczyńska et al. (2009). However the internal structure of asteroids is presently unclear and newly obtained values may serve as an input to the theories of the Solar System evolution. Higher values of the bulk density are due to non-convex shape of the system. The more shape deviates from a sphere the larger density value we get.

The shape and size of Lundia could be refined given direct measurements, like stellar occultation events. Predictions for 2017 based on new GAIA DR1 catalog yield two events on 27 April and 28 May 2017. Unfortunately Lundia’s small size makes accurate prediction difficult, as uncertainty of star position on the level of 7 mas translates into 15 km uncertainty in the position on Earth which is about the size of the Lundia system. Nevertheless, such observations could put better constraints on asteroid’s size and density.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union’s Horizon 2020 Research and Innovation Programme, under Grant Agreement no 687378. This work was partially supported by grant no. 2014/13/D/ST9/01818 from the National Science Centre, Poland.

This paper uses observations made at the South African Astronomical Observatory (SAAO). The reduction of CCD frames from Borowiec and SAAO were performed with the CCLR STARLINK package.

G. Apostolovska gratefully acknowledge observing grant support from the Institute of Astronomy and Rozhen National Astronomical Observatory, Bulgarian Academy of Sciences.

REFERENCES

Bartczak P., Michałowski T., Santana-Ros T., Dudziński G., 2014, MNRAS, 443, 1802
Birlan M., Nedelcu D. A., Popescu M., Vernazza P., Colas F., Kryszczyńska A., 2014, MNRAS, 437, 176
Britt D. T., Consolmagno G. J., 2003, Meteoritics and Planetary Science, 38, 1161
Britt D. T., Yeomans D., Housen K., Consolmagno G., 2002, Asteroid Density, Porosity, and Structure. pp 485-500
Carry B., 2012, Planet. Space Sci., 73, 98
Catullen E., Clark J., 1978, Computer-Aided Design, 10, 350
Descamps P., 2010, Icarus, 207, 758
Florczak M., Lazzaro D., Duffard R., 2002, Icarus, 159, 178
Kryszczyńska A., Kwiatkowski T., Hirsch R., Polinska M., Kaminiski K., Marchiniak A., 2005, Central Bureau Electronic Telegrams, 239
Kryszczyńska A., et al., 2009, A&A, 501, 769
Marchis F., et al., 2012, Icarus, 221, 1130
McCausland P. J. A., Flemming R. L., 2006, in Mackwell S., Stansbery E., eds, Lunar and Planetary Science Conference Vol. 37, 37th Annual Lunar and Planetary Science Conference.
Michałowski T., et al., 2004, A&A, 416, 353
Pravec P., Harris A. W., 2007, Icarus, 190, 250

This paper has been typeset from a TeX/LaTeX file prepared by the author.
Figure 7. $xz$, $yz$, $xy$, $-xz$, $-yz$, $-xy$ projections of the Lundia model.
Figure 8. Observations (black crosses) versus synthetic lightcurves of the model (solid red line).