

Synergistic studies of asteroids: photometry, thermophysical modelling, and occultations

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- Gaca, T. Polakis, J. J. Sanabria, T. Santana-Ros, B. Skiff, K. Sobkowiak,

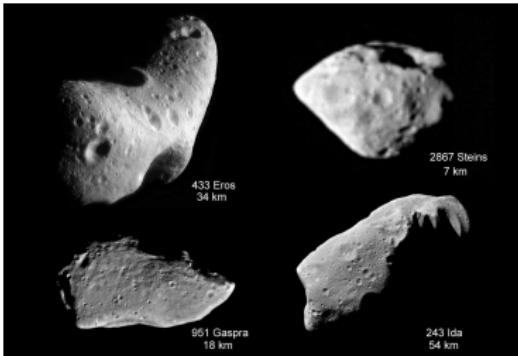
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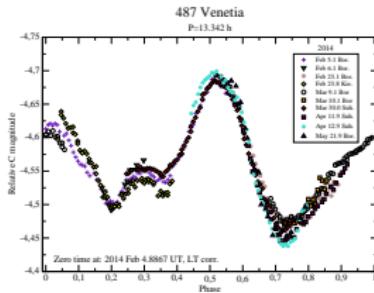
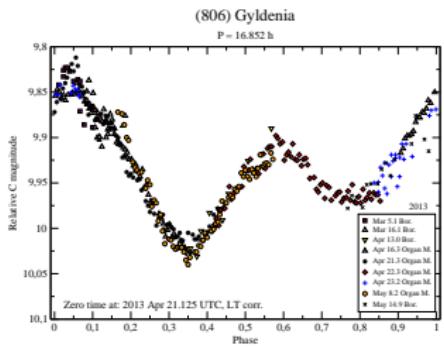
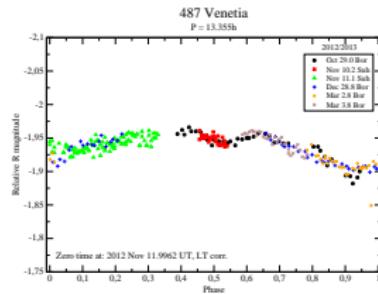
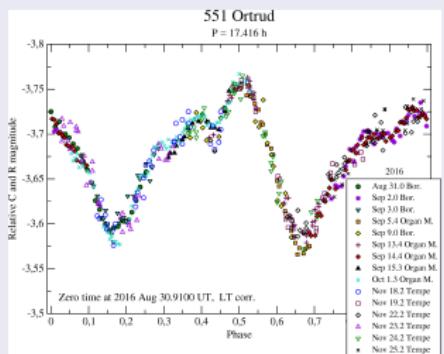
40-years of SOPiZ PTMA, Warsaw, 28 April 2019

Why study asteroids?

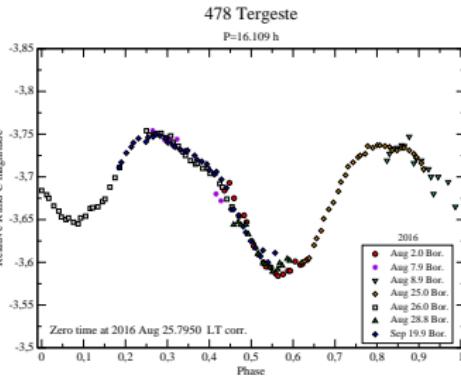
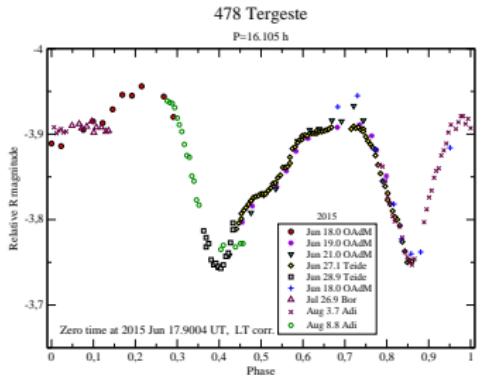
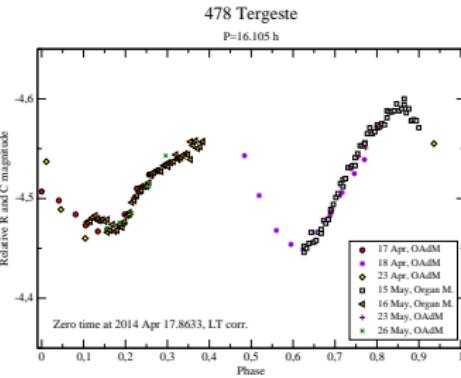
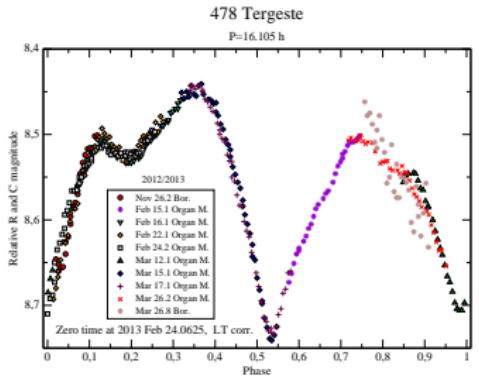
- Leftovers from Solar System formation
- Record of conditions and composition of protoplanetary disc
- Record of intensive migrations and heavy bombardment epochs
- Link between meteorites and their parent bodies
- Differentiated and hydrously altered little worlds
- Grouped in asteroid families and clusters
- Record of thermal recoil forces (Yarkovsky and YORP)
- Varying in thermal properties of regolith and deeper sub-surface layers



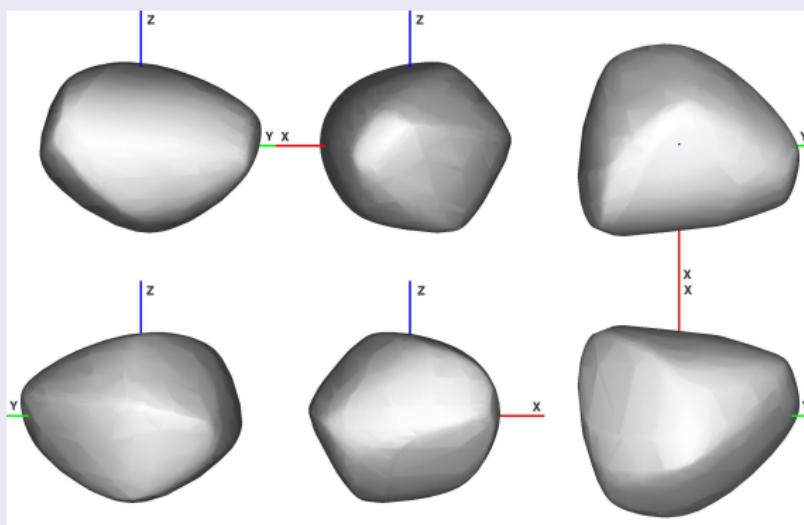
Asteroid lightcurves



478 Tergeste - lightcurves



478 Tergeste - lighcurve inversion model



$$P = 16.10311 \pm 0.0001 \text{ h}; \text{rmsd} = 0.011 \text{ mag}$$

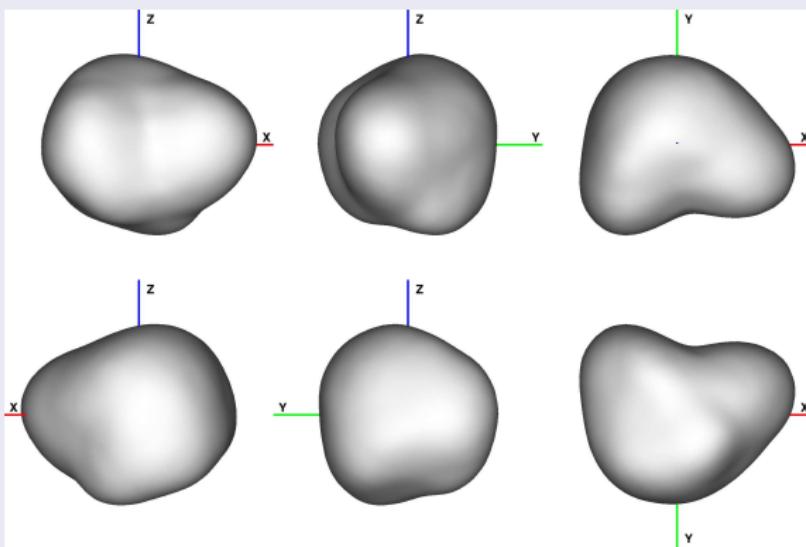
$$\lambda_{p1} = 2^\circ \pm 10^\circ$$

$$\beta_{p1} = -42^\circ \pm 6^\circ$$

$$\lambda_{p2} = 216^\circ \pm 8^\circ$$

$$\beta_{p2} = -56^\circ \pm 5^\circ$$

478 Tergeste - SAGE model (Shaping asteroids with Genetic Evolution)



$$P = 16.10312 \pm 0.00001 \text{ h}; \text{rmsd} = 0.012 \text{ mag}$$

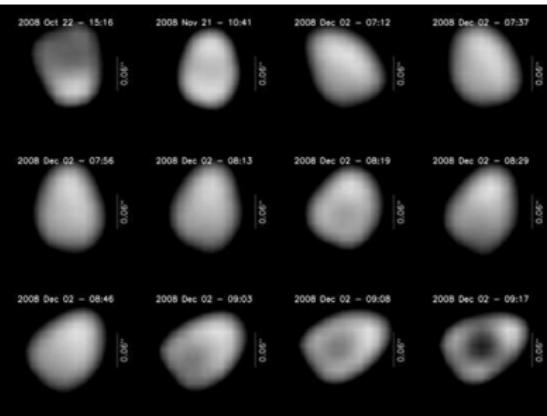
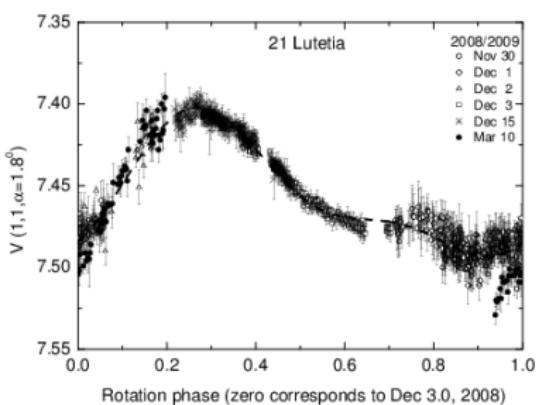
$$\lambda_{p1} = 4^\circ \pm 5^\circ$$

$$\lambda_{p2} = 218^\circ \pm 5^\circ$$

$$\beta_{p1} = -43^\circ \pm 5^\circ$$

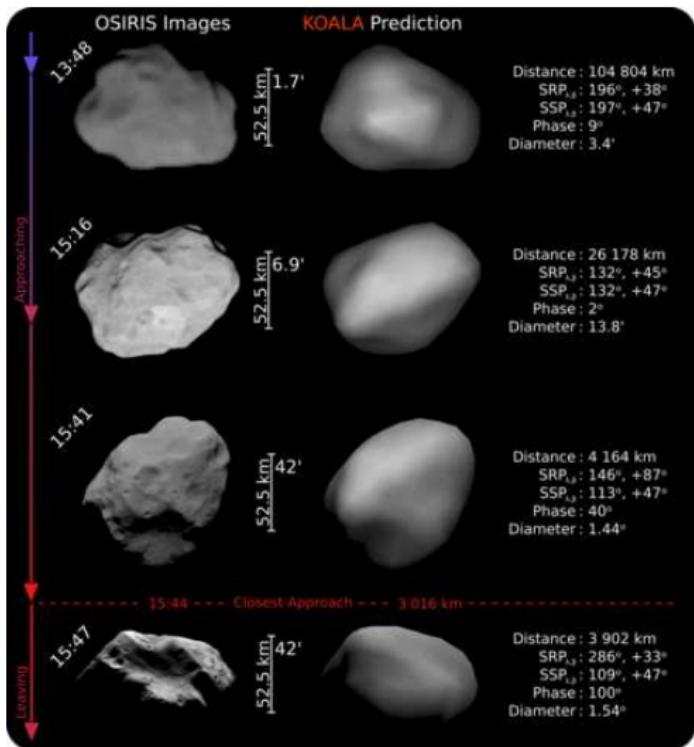
$$\beta_{p2} = -56^\circ \pm 5^\circ$$

21 Lutetia - lightcurves and Adaptive Optics images



Belskaya et al. 2010, Carry et al. 2010

21 Lutetia - KOALA model (Knitted Occultation, Adaptive-optics, and Lightcurve Analysis)



Asteroid studies



Models



Selection effects



Shape models & occultations



TPM



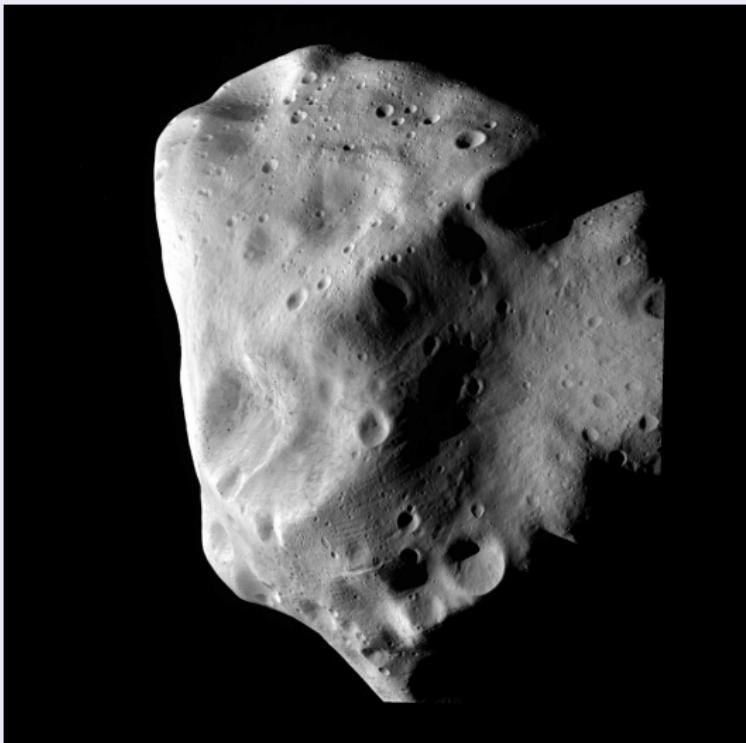
Results



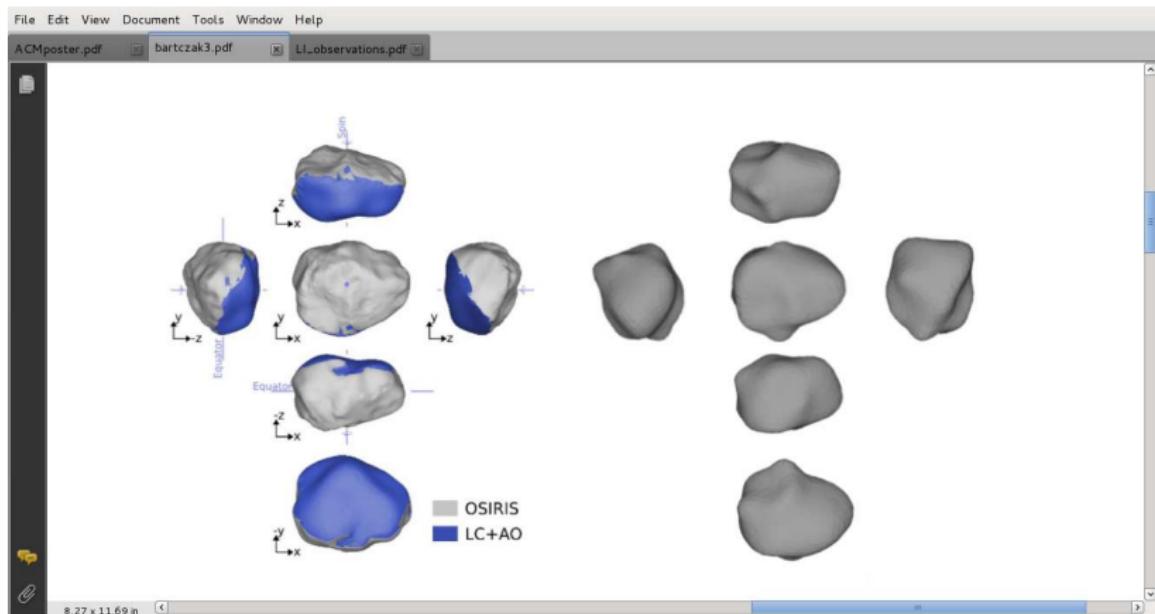
Summary



21 Lutetia as seen by the Rosetta spacecraft



21 Lutetia - model comparison



Carry et al. 2010, Bartczak et al. 2014

162 173 Ryugu - the best model prior to Hayabusa mission

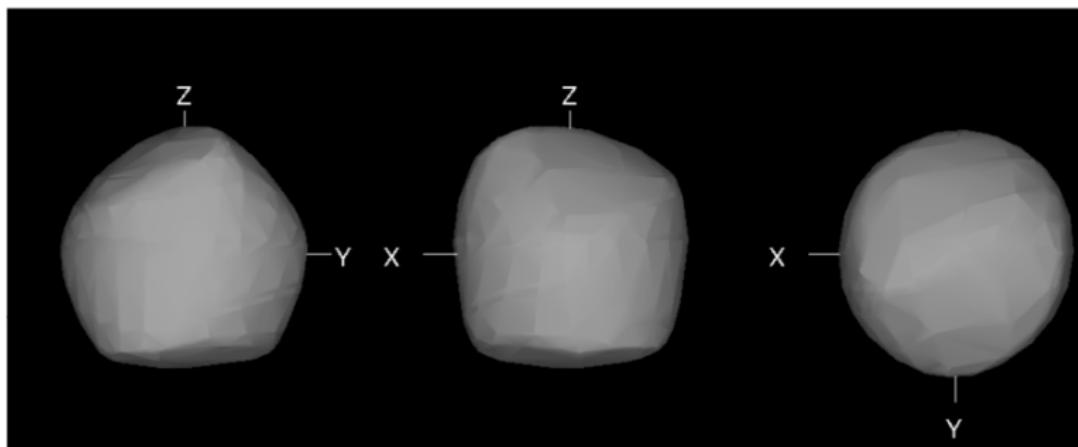


Fig. 8. The formally best-fit shape model of Ryugu for pole direction $(340^\circ, -40^\circ)$.

Müller et al. 2017

Asteroid studies
○○

Models
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Selection effects
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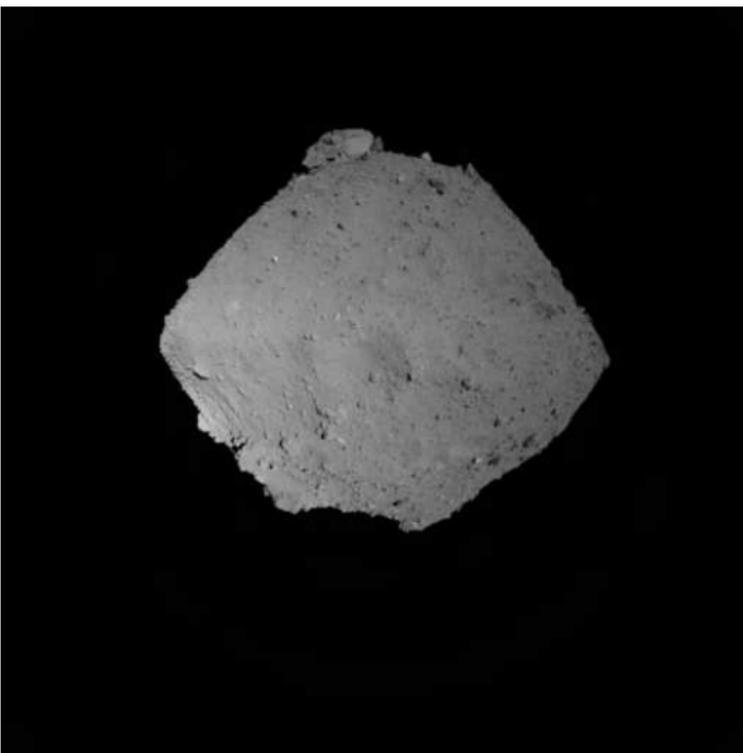
Shape models & occultations
○○○○○

TPM
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Results
○○○○○○○○○

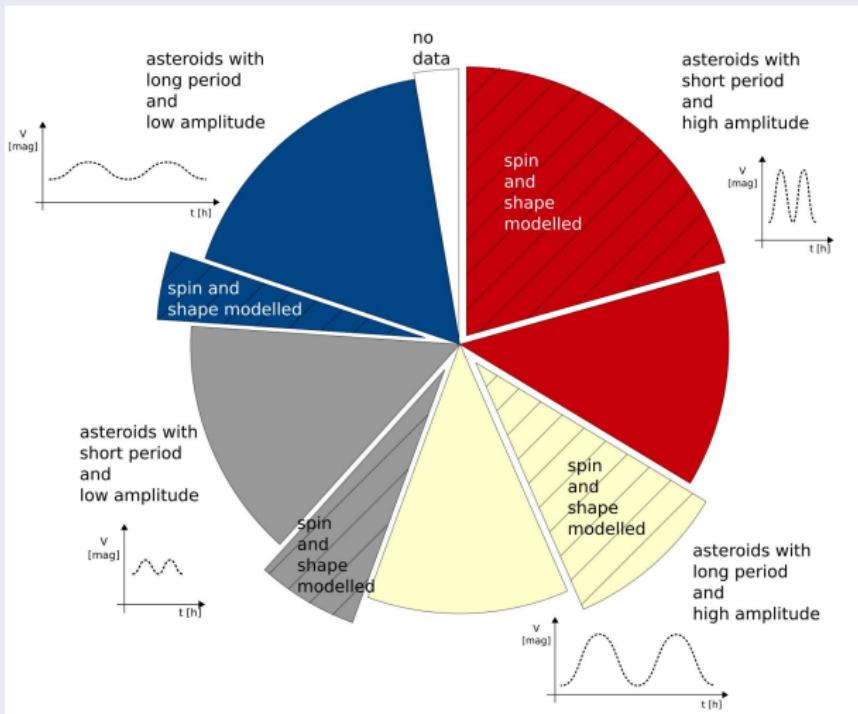
Summary
○

162 173 Ryugu - in reality



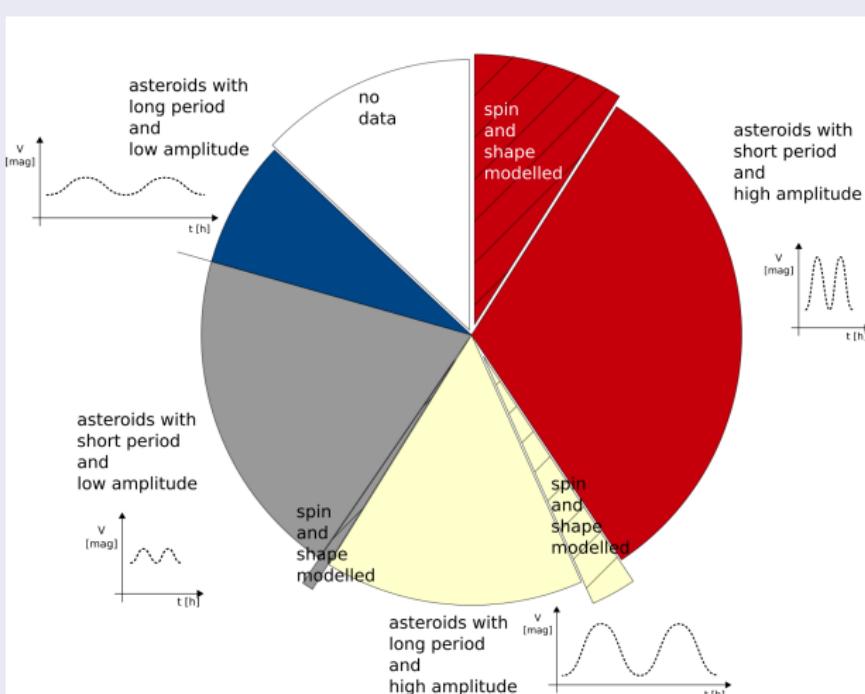
JAXA

Selection effects in MBA models



All 1230 asteroids with $H \geq 11$ mag
 Division values: $P = 12$ h, $a_{max} = 0.25$ mag.

Selection effects in fainter MBA models



All 2274 asteroids with $11 < H \leq 13$ mag
 Division values: $P = 12$ h, $a_{max} = 0.25$ mag.



Observation planner for project against biases

[asteroids.2614536-0.web-hosting.es](#)



Szukaj



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Observation planner



Anna Marciniak

Administrator

Website map



Home



Suggested targets



Observation sites



Observation runs

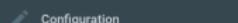


About this project...

Administrator menu



Targets



Configuration



Ephemeris

Observation planner

Against the bias in spins and shapes of asteroids

Search targets for observation

October 2018

Su	Mo	Tu	We	Th	Fr	Sa
30	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31	1	2	3
4	5	6	7	8	9	10

Borowiec Observatory

Lon: 17° 04' 36.00" E Lat: 52° 16' 38.00" N

2018 / Observation planner / Against the bias in spins and shapes of asteroids

Observation planner, site selection





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Administrator

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Administrator menu

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- [Ephemeris](#)

Observation sites (Anna Marciniak) [+](#)

Select user:

Anna Marciniak

Name	Latitude	Longitude	Altitude (m)	Elev. (deg)	Min mag	Max Obs.	Future obs.	Actions
□ Borowiec Observatory	52° 16' 38.00" N	17° 04' 36.00" E	80 m	25°	15.1	0	4	edit remove
□ Observatori Astronomic del Montsec	42° 03' 05.00" N	00° 43' 46.00" E	1570 m	20°	18.0	0	0	edit remove
□ Mt. Suhora Observatory	49° 34' 09.00" N	20° 04' 03.00" E	1009 m	25°	17.0	0	0	edit remove
□ JKU Astronomical Observatory, Kielce	50° 52' 27.00" N	20° 38' 00.00" E	400 m	25°	13.0	0	0	edit remove
□ Derenivka, Ukraine	48° 33' 48.00" N	22° 27' 13.00" E	220 m	25°	14.0	0	0	edit remove
□ Adiyaman, Turkey	38° 13' 31.00" N	37° 45' 06.00" E	690 m	25°	14.0	0	0	edit remove
□ Teide Observatory	28° 17' 54.00" N	16° 30' 34.00" W	2300 m	25°	19.0	0	0	edit remove
□ Roque de los Muchachos, La Palma	28° 45' 30.00" N	17° 52' 48.00" W	2400 m	25°	19.0	0	0	edit remove
□ Winer Observatory, Arizona	31° 39' 56.00" N	110° 36' 06.00" W	1500 m	20°	18.0	0	0	edit remove
□ Organ Mesa Observatory, New Mexico	32° 18' 52.00" N	106° 46' 44.00" W	1200 m	25°	15.0	0	0	edit remove
□ Bisei Spaceguard Center, Japan	34° 40' 20.00" N	133° 32' 40.00" E	400 m	25°	14.0	0	0	edit remove
□ Pic du Midi, France	42° 56' 11.00" N	00° 08' 31.00" E	2900 m	25°	17.0	0	0	edit remove
□ Kitt Peak National Observatory	31° 58' 48.00" N	111° 36' 00.00" W	2100 m	25°	19.0	0	0	edit remove

Observation planner, suggested targets

[◀](#) ⓘ | asteroids.2614536-0.web-hosting.es/p_suggested.php?SEL SITE_3=on

[⟳](#) ⓘ Szukaj



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☰ Observation planner

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Suggested targets (2018-10-05)

Select date: → 2018-10-05

Borowiec Observatory

Lon: 17° 04' 36.00" E Lat: 52° 16' 38.00" N Alt: 80 m

Borowiec Observatory - Twilight (17:32 - 03:48)

Object	Mag	Period(h)	U	Altitude Beg./Mid/End	Hours visible	Begin (UT)	End (UT)	Stat.	Moon	Actions
(366) Vincentina	13.4	17.336	2	25° / 60° / 37°	09h 06m	18:42	03:48	113°		
(397) Vienna	12.9	15.480	3	25° / 52° / 57°	06h 02m	21:46	03:48	75°		
(476) Hedwig	12.8	27.246	3	25° / 65° / 48°	09h 13m	18:35	03:48	103°		
(524) Fidelio	14.3	14.171	3	25° / 50° / 69°	05h 19m	22:29	03:48	54°		
(527) Euryanthe	14.5	26.060	2	25° / 43° / 36°	05h 48m	22:00	03:48	96°		
(537) Pauly	14.2	16.168	3	25° / 45° / 47°	05h 18m	22:30	03:48	79°		
(538) Friederike	15.0	46.728	3	25° / 42° / 53°	03h 48m	00:00	03:48	50°		
(903) Nealley	15.0	21.600	2	25° / 42° / 33°	06h 01m	21:47	03:48	101°		
(677) Aaltje	14.6	16.608	3	29° / 33° / 25°	04h 10m	17:32	21:43	166°		
(766) Moguntia	14.0	4.816	3	25° / 45° / 25°	07h 40m	18:54	02:35	135°		
(894) Erda	13.8	4.689	3	25° / 38° / 25°	06h 13m	18:11	00:24	156°		
(1224) Fantasia	13.0	4.995	3	26° / 58° / 25°	09h 47m	17:32	03:20	132°		
(2151) Hadwiger	14.4	5.872	3	25° / 46° / 25°	07h 44m	19:45	03:29	123°		



Observation planner, sky charts

astroids.2614536-0.web-hosting.es/p_details.php?id_site=3&id_target=903&date=2018-10-05 | Szukaj

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≡ Observation planner



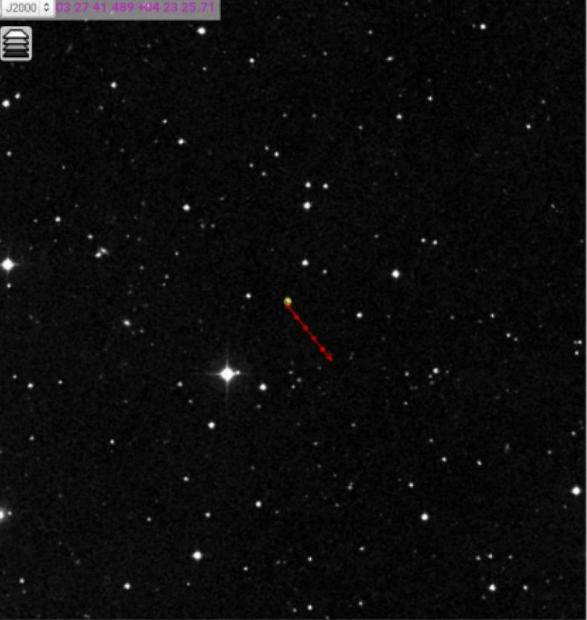
Anna Marciniaik
Administrator

- [Website map](#)
- [!\[\]\(eeea24db2ce28d592481b9a8bc516056_img.jpg\) Home](#)
- [!\[\]\(c04675ca808bb91cef7d82cf2875eedd_img.jpg\) Suggested targets](#)
- [!\[\]\(cdcb02c06f9ee0023c21dec74c98f17b_img.jpg\) Observation sites](#)
- [!\[\]\(2c50f7b0a1734f15d77eae4a697756cb_img.jpg\) Observation runs](#)
- [!\[\]\(d9e8c2e4e63e3b1ceb426eab9aa60ee8_img.jpg\) About this project...](#)
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- [Administrator menu](#)
- [!\[\]\(e5c2f2fa06b3e8a46ae21fa771c55be5_img.jpg\) Targets](#)
- [!\[\]\(2ea54475c396ef2efa908ed12875e94d_img.jpg\) Configuration](#)
- [!\[\]\(9088a8e7d52a8ada6c0ba4cbd63a6731_img.jpg\) Ephemeris](#)

Observation details Borowiec Observatory, 2018-10-05, Nealley(903)

Finder chart

J2000 03:27:41.489 +04:23:25.71



DSS-Real

ALT(mid)	41.8°
Mag	15.0
Moon	100.7° / 24%
Date(st.)	2018-10-05 21:47 UT
Date(mid)	2018-10-06 01:24 UT
Date(end)	2018-10-06 03:48 UT
POS(st.)	03:27:48.95 +04:24:47.1 / Alt: 25°
POS(mid)	03:27:46.04 +04:23:53.0 / Alt: 42°
POS(end)	03:27:44.09 +04:23:16.7 / Alt: 33°
One star is close to the path	
Stars	03:27:48.97 +04:24:54.9 / Mag: 15.5

Object Altitude

Altitude graph for Borowiec Observatory



The graph shows the altitude of the object in degrees (deg) over time. The x-axis represents time, and the y-axis represents altitude from 60 to 90 degrees. The graph shows a peak altitude around 88 degrees at approximately 03:27:48.97.

Observation planner, phase coverage

(Szukaj)

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Observation planner

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Phase coverage graph for: (903) Nealley

Period: 21.600h = 0.900d

2018-10-02 0.000000 -- 0.277778
|*****-----|

2018-10-03 0.0 -- 0.049383, 0.740741 -- 1.0
|-----*****|

2018-10-03 0.157408 -- 0.388889
|=====*****|

////////// you can cover tonight //////////

2018-10-05 0.331430 -- 0.610301
|-----*****|

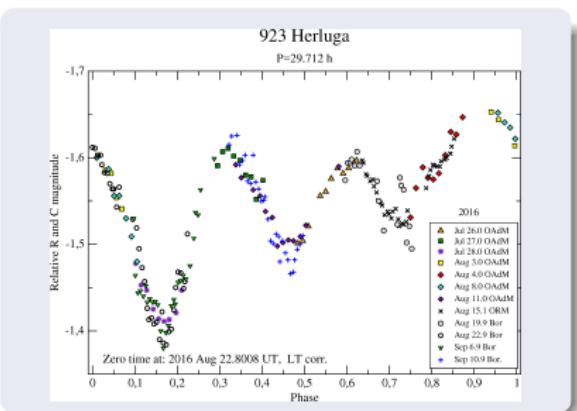
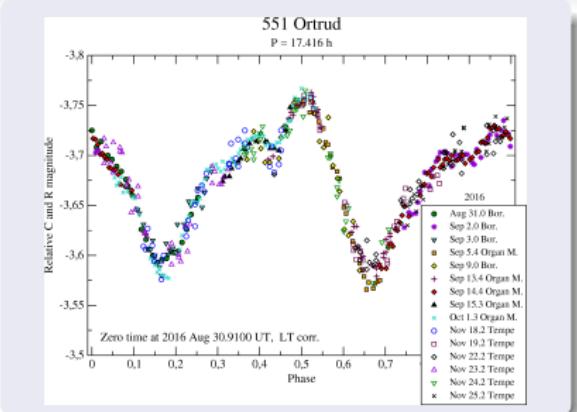
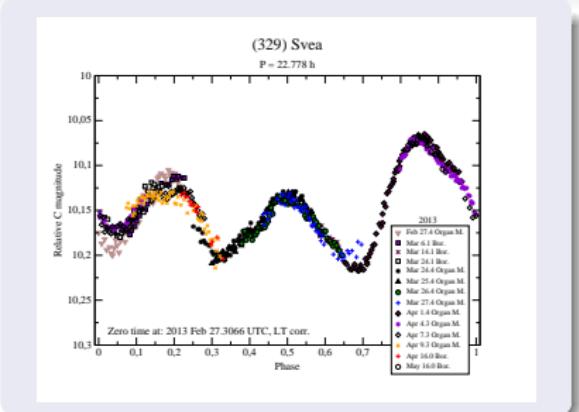
Select date: 2018-10-05
T 04° 36.00' E Lat: 52° 16' 38.00" N Alt: 80 m

Target	Stat.	Moon	Actions
68	113°		
48	75°		
38	103°		
48	54°		
48	96°		
(537) Pauly	14.2	16.168	3 25° / 45° / 47° 05h 18m 22:30 03:48 79°
(538) Friederike	15.0	46.728	3 25° / 42° / 53° 03h 48m 00:00 03:48 50°
(903) Nealley	15.0	21.600	2 25° / 42° / 33° 06h 01m 21:47 03:48 101°
(677) Aaltje	14.6	16.608	3 29° / 33° / 25° 04h 10m 17:32 21:43 166°
(786) Moguntia	14.0	4.816	3 25° / 45° / 25° 07h 40m 18:54 02:35 135°
(894) Erda	13.8	4.689	3 25° / 38° / 25° 06h 13m 18:11 00:24 156°
(1224) Fantasia	13.0	4.995	3 28° / 58° / 25° 09h 47m 17:32 03:20 132°

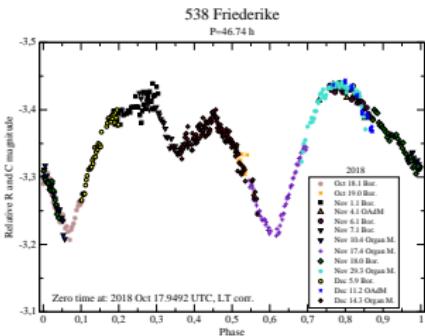
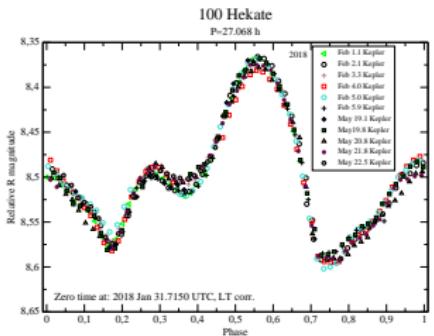
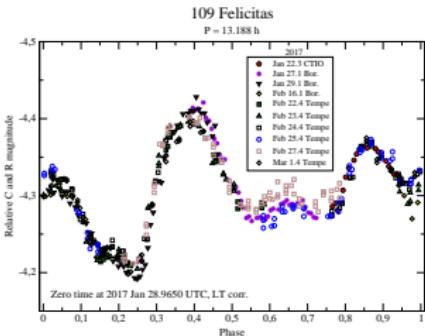
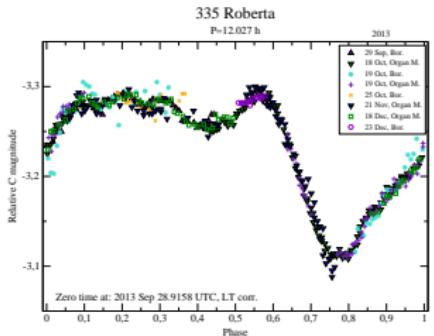
OK

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Selected lightcurves



Selected lightcurves



Fitting asteroid shape models to stellar occultation chords

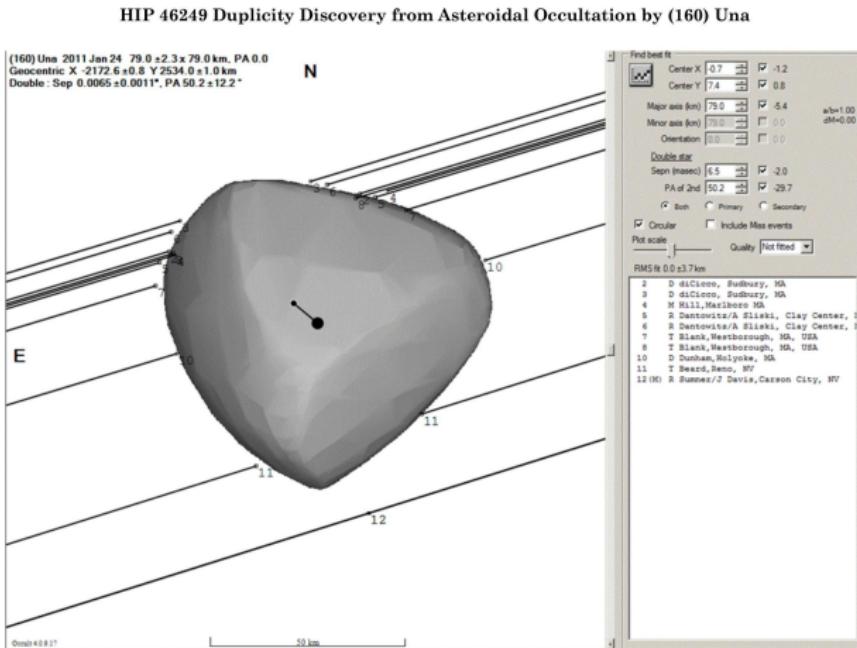


Figure: Occultation chords of a star HIP 46249 occulted by asteroid 160 Una, with the lightcurve inversion model by Marciniak et al. (2009) superimposed. This event independently confirmed spin parameters and shape model from the lightcurve inversion method (George et al. 2011).

Interactive Service for Asteroid Models

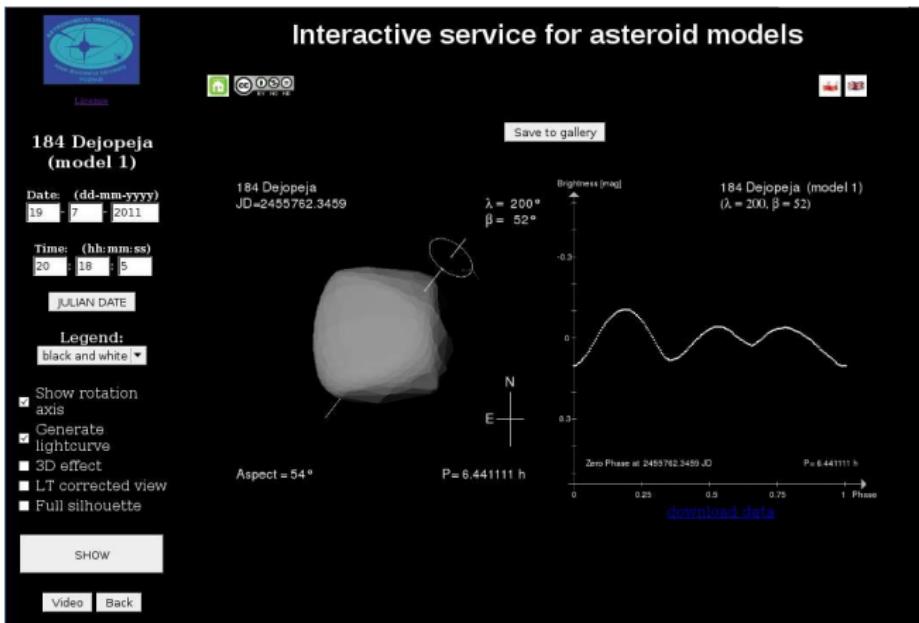
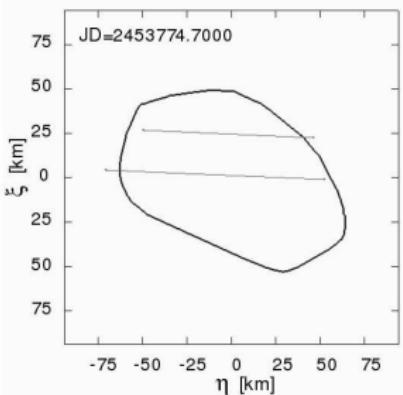


Figure: ISAM service for sky-plane orienting astroid shape models. Also used for lightcurve generation, 3D views and animations and more.

isam.astro.amu.edu.pl

Fitting asteroid shape models to (poorly covered) occultations

127 Johanna (model 1) 2006-02-08



127 Johanna (model 2) 2006-02-08

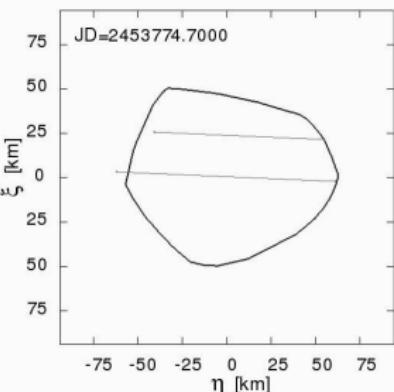
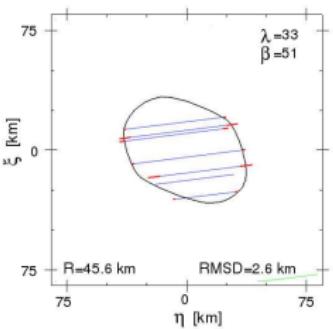


Figure: Fitting to occultation with only two positive chords. Pole, shape, and size are poorly constrained.

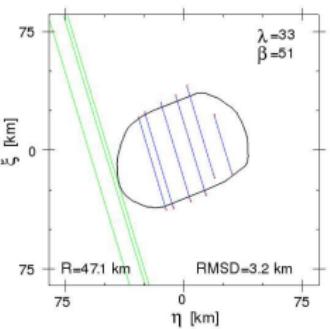
Marciniak et al., 2012

Fitting the shape models to (great) occultations

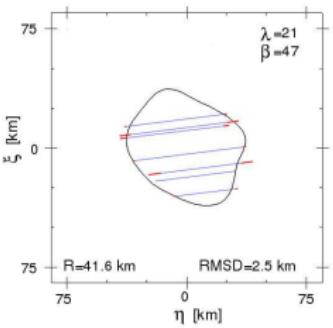
329 Svea (CONVEX) 2011-12-28



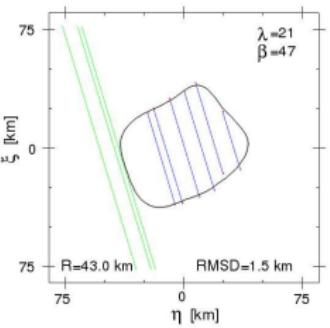
329 Svea (CONVEX) 2013-03-07



329 Svea (SAGE) 2011-12-28



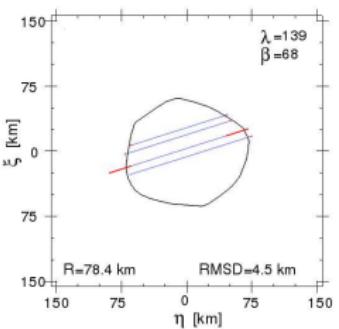
329 Svea (SAGE) 2013-03-07



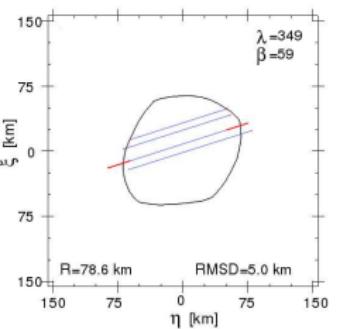
Diameters of equivalent volume sphere:
 CONVEX (2011): $72 \pm 4 \text{ km}$; CONVEX (2013): $74 \pm 5 \text{ km}$
 SAGE (2011): $70 \pm 4 \text{ km}$; SAGE (2013): $72 \pm 3 \text{ km}$

Fitting the shape models to good occultations

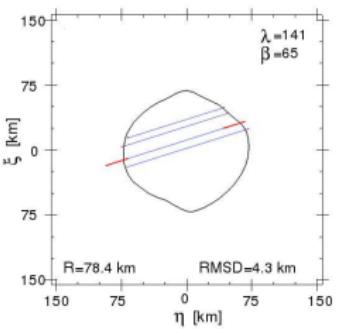
159 Aemilia (CONVEX) 2009-05-02



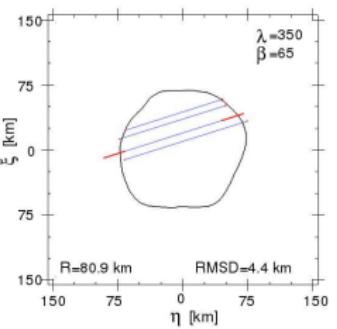
159 Aemilia (CONVEX) 2009-05-02



159 Aemilia (SAGE) 2009-05-02



159 Aemilia (SAGE) 2009-05-02

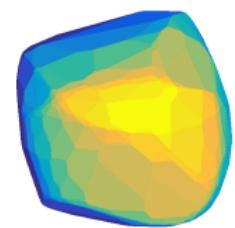


Diameters of equivalent volume sphere:

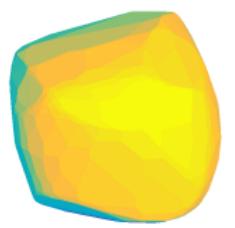
CONVEX (pole 1): $130 \pm 7 \text{ km}$; CONVEX (pole 2): $130 \pm 8 \text{ km}$
 SAGE (pole 1): $135 \pm 7 \text{ km}$; SAGE (pole 2): $138 \pm 7 \text{ km}$

Thermophysical modelling

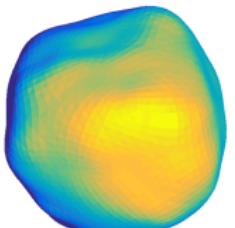
Insolation and surface temperature distribution: (159) Aemilia



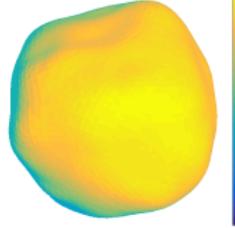
120
100
80
60
40
20
0



200
160
120
80
40
0

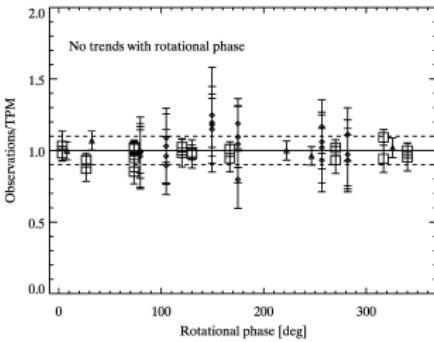
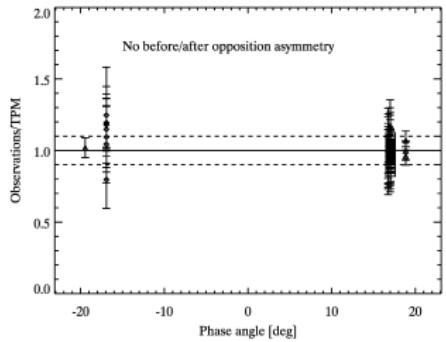
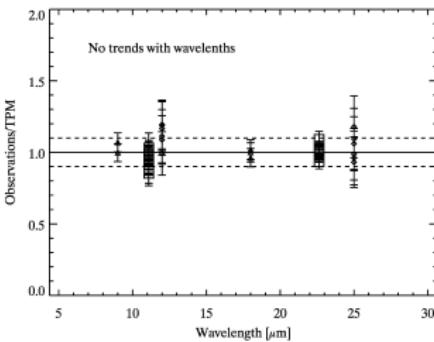
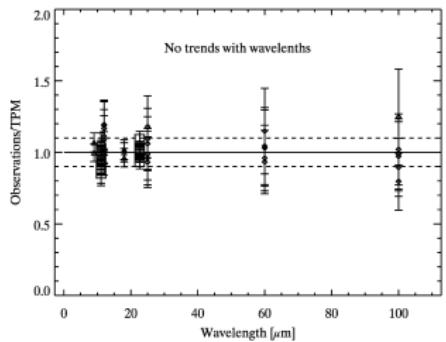


120
100
80
60
40
20
0



200
160
120
80
40
0

O-C plots for (159) Aemilia model applied in TPM



Target	Rotation period [h]	Taxonomic type	Radiometric solution for combined data.		
			Diameter [km]	Albedo	Thermal inertia [$\text{Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$]
159 Aemilia	24.4787 ± 0.0001	Ch	137 ± 8	0.054 ± 0.015	50 ± 50
227 Philosophia	26.4614 ± 0.0001	C	101 ± 5	0.041 ± 0.005	125 ± 90
329 Svea	22.7670 ± 0.0001	C	78 ± 4	0.055 ± 0.015	75 ± 50
478 Tergeste	16.10312 ± 0.00003	L	87 ± 6	0.15 ± 0.02	75 ± 45
487 Venetia	13.34133 ± 0.00002	S	70 ± 4	0.21 ± 0.02	100 ± 75

Asteroid studies



Models



Selection effects



Shape models & occultations



TPM



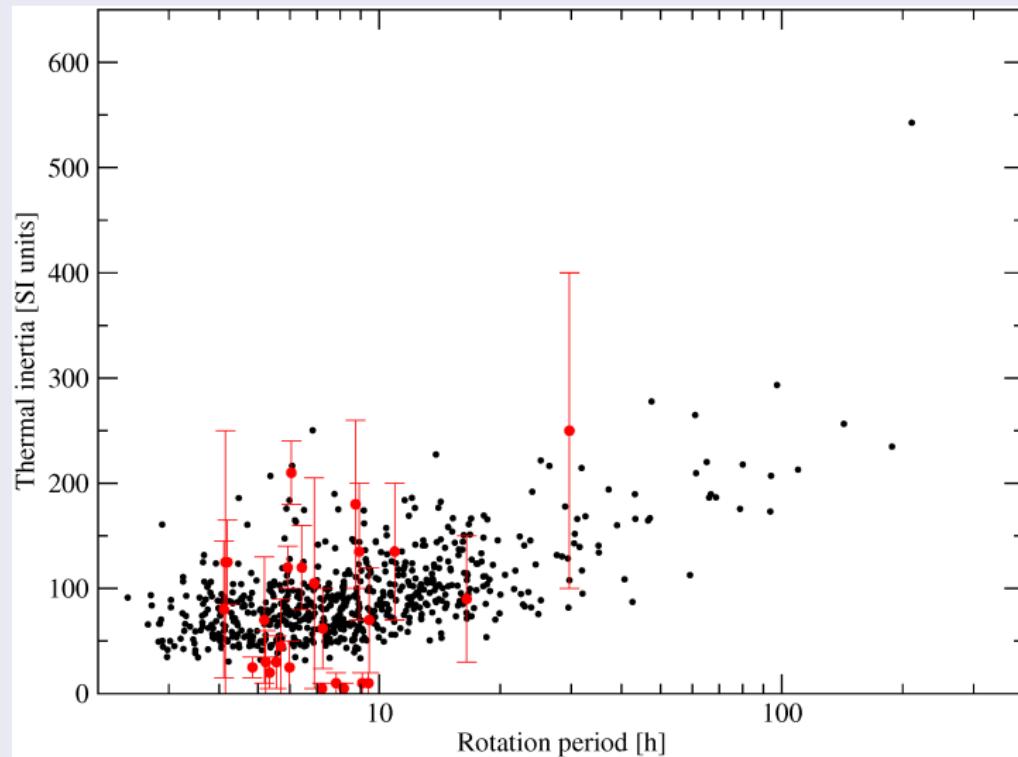
Results



Summary



Thermal inertia of Main Belt Asteroids



Asteroid studies



Models



Selection effects



Shape models & occultations



TPM



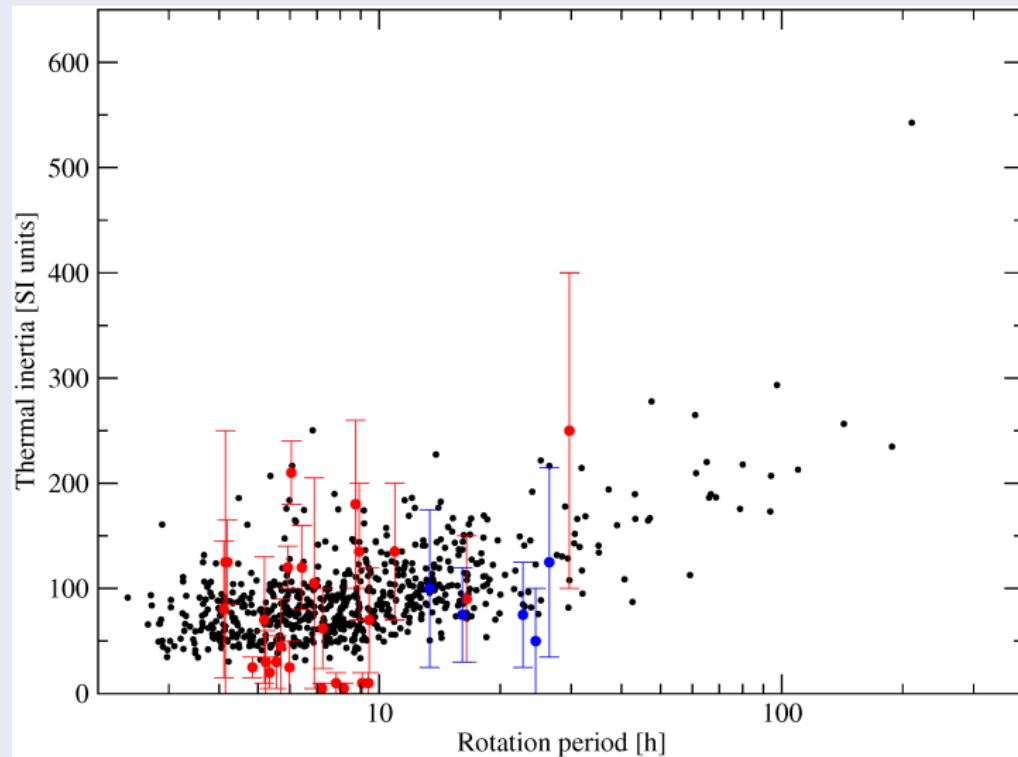
Results



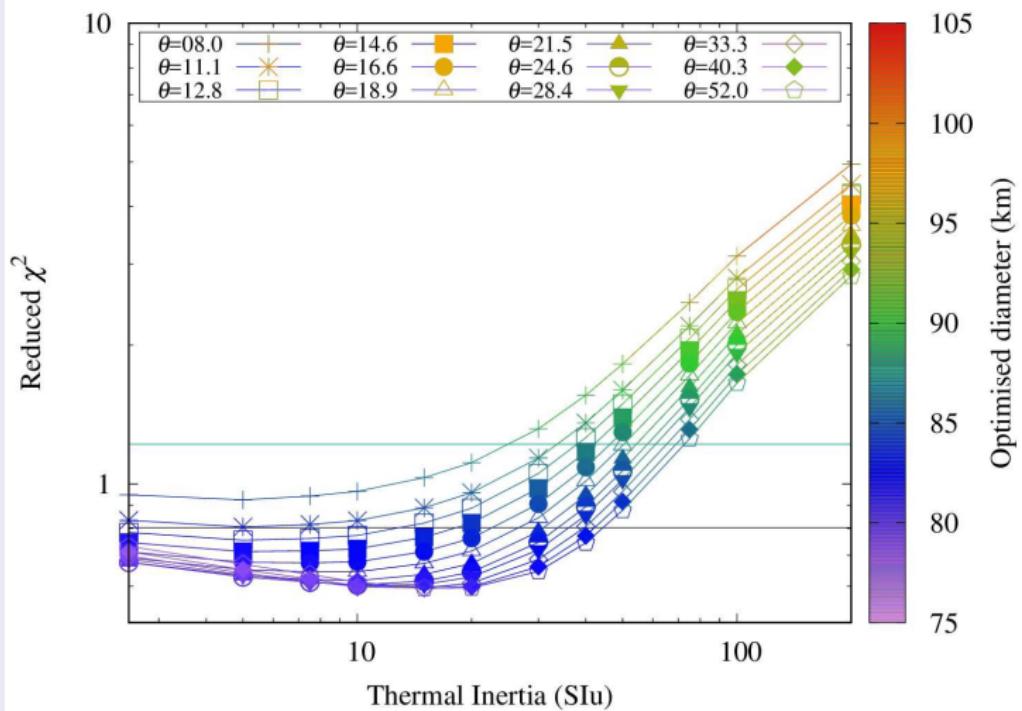
Summary



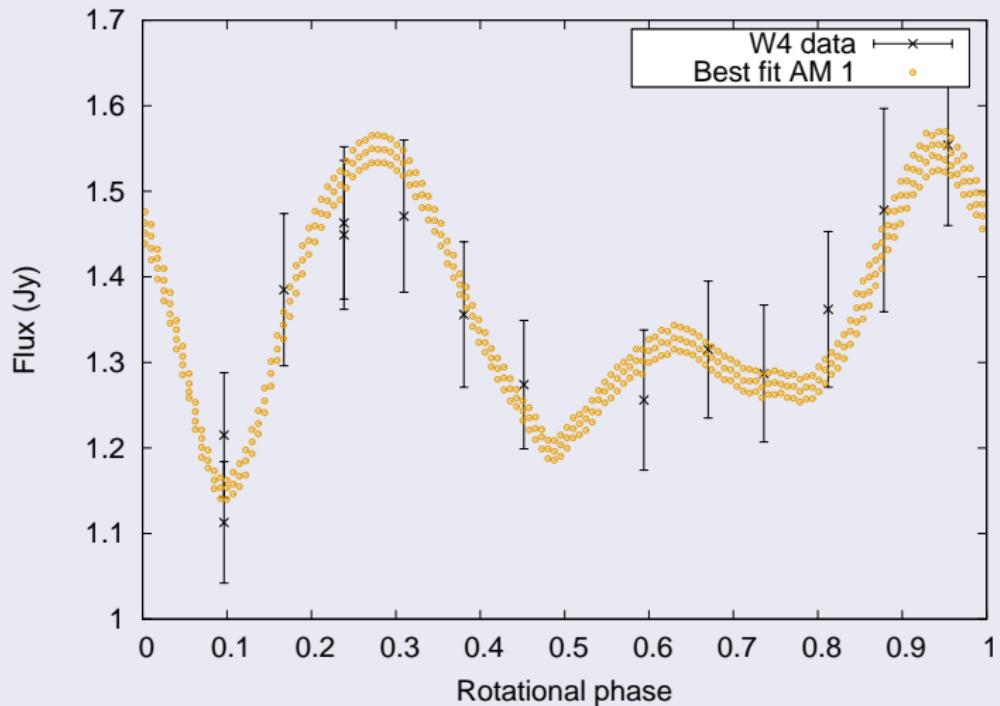
Thermal inertia of slow rotators



(195) Eurykleia model in thermophysical modelling



Thermal lightcurve fit to WISE W4 data (target: 673 Edda)



Asteroid studies



Models



Selection effects



Shape models & occultations



TPM



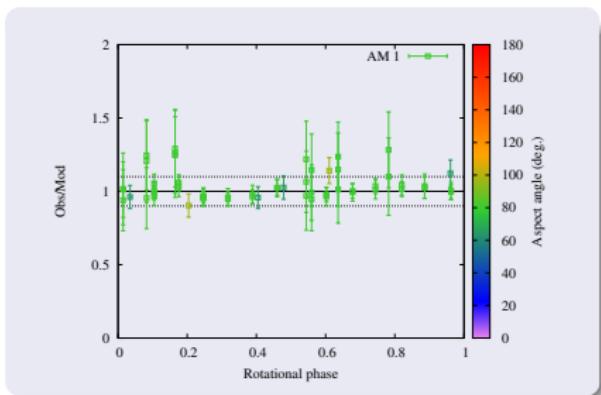
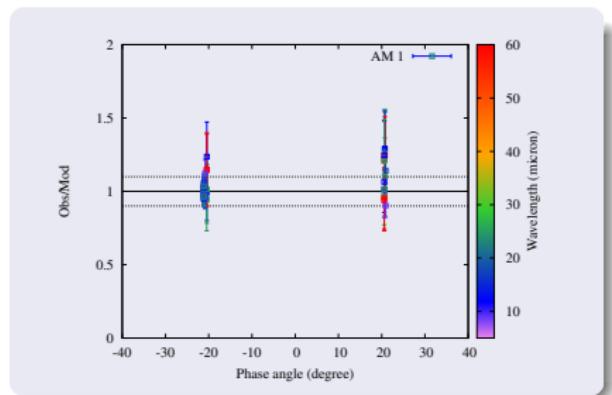
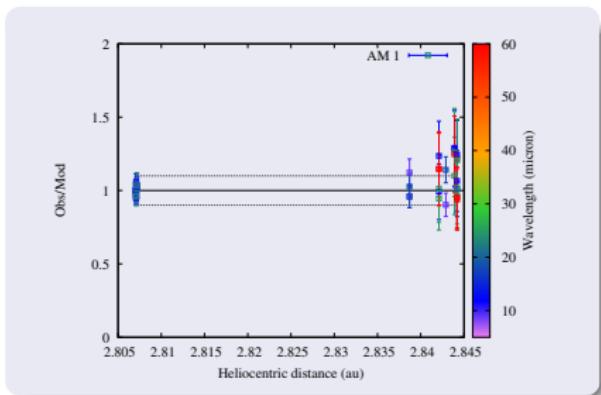
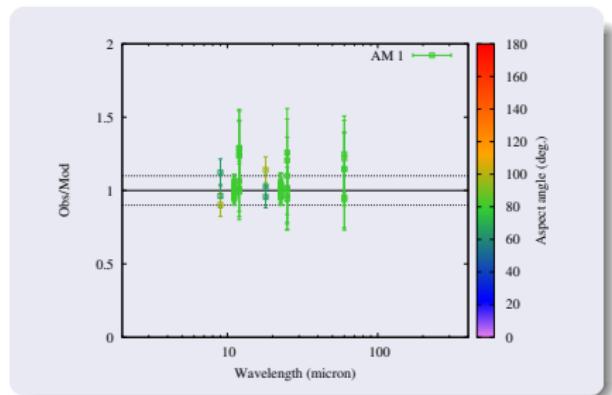
Results



Summary



O-C plots for (673) Edda model applied in TPM



Asteroid studies



Models



Selection effects



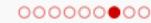
Shape models & occultations



TPM



Results



Summary



Summary of TPM results for (673) Edda.

Shape model	IR data subset	$\bar{\chi}_m^2$	$D \pm 3\sigma$ (km)	$\Gamma \pm 3\sigma$ (Slu)	Roughness (rms)
AM 1	All data	0.47	38^{+6}_{-2}	3^{+67}_{-3}	Med.-high (0.50)
AM 1 sphere	All data	1.83	38	5	Med.-high (0.39)
AM 2	All data	0.59	38^{2+}_{-2}	3^{+37}_{-3}	Extr. high (1.0)
AM 2 sphere	All data	1.76	38	10.	Medium (0.44)

Target	Rotation period [h]	Taxonomic type	Radiometric solution for combined data.		
			Diameter [km]	Albedo	Thermal inertia [SI units]
100 Hekate	27.07027 ±0.00006	S	87 ⁺⁵ ₋₄	0.22 ^{+0.03} _{-0.03}	4 ⁺⁶⁶ ₋₂
109 Felicitas	13.190550 ±0.000004	Ch	85 ⁺⁷ ₋₅	0.065 ^{+0.008} _{-0.01}	40 ⁺¹⁰⁰ ₋₃₆
195 Eurykleia	16.52178 ±0.00002	Ch	87 ⁺¹¹ ₋₉	0.06±0.02	15 ⁺⁵⁵ ₋₁₅
301 Bavaria	12.24090 ±0.00001	C	55 ⁺² ₋₂	0.047 ^{+0.004} _{-0.003}	45 ⁺⁶⁰ ₋₃₀
335 Roberta	12.02713 ±0.00003	B	98 ⁺¹⁰ ₋₁₁	0.046 ^{+0.014} _{-0.008}	unconstrained
380 Fiducia	13.71723 ±0.00002	C	72 ⁺⁹ ₋₅	0.057 ^{+0.009} _{-0.012}	10 ⁺¹⁴⁰ ₋₁₀
468 Lina	16.47838 ±0.00003	CPF	69 ⁺¹¹ ₋₄	0.052 ^{+0.006} _{-0.014}	20 ⁺²⁸⁰ ₋₂₀
538 Friederike	46.739 ±0.001	C	77 ⁺⁴ ₋₂	0.06±0.01	10 ⁺²⁵ ₋₁₀
653 Berenike	12.48357 ±0.00003	K	46 ⁺⁴ ₋₂	0.18 ^{+0.02} _{-0.03}	40 ⁺¹²⁰ ₋₄₀
673 Edda	22.33411 ±0.00004	S	38 ⁺⁶ ₋₂	0.13 ^{+0.03} _{-0.05}	3 ⁺⁶⁷ ₋₃
834 Burnhamia	13.87594 ±0.00002	GS	67 ⁺⁸ ₋₆	0.074 ^{+0.014} _{-0.016}	20 ⁺³⁰ ₋₂₀

Asteroid studies



Models



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TPM



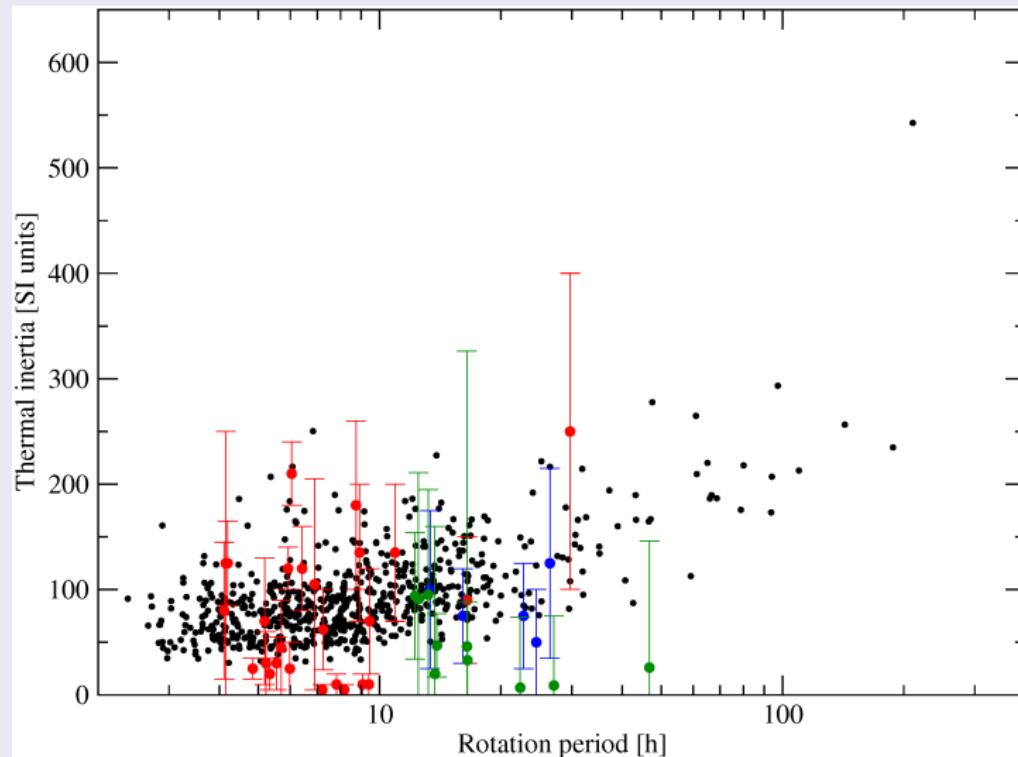
Results



Summary



Thermal inertia of slow rotators



Summary

- Selection effects: spin and shape models mainly available for short-period, elongated asteroids with extreme obliquities
- Biased spatial spin axis and size-frequency distributions, lack of detailed models for slow rotators
- Our targeted survey of 100 long-period, low-amplitude MB asteroids. Gathered over 10 000 hours of lightcurve data in 20 stations worldwide (+ Kepler).
- Modelled 16 targets from this sample, scaled by TPM using IR data from IRAS, AKARI and WISE
- Stellar occultations provide valuable constraints on spin/shape solutions of asteroids
- Occultations allow precise size determinations -> Density!
- ... or to discover rings...
- Found high, medium and very low thermal inertias in TPM
- Differences due to sub-surface temperatures and different material properties?
- Indication of fresh and old surfaces connected with formation age and/or size?
- Synergic approach gives broader picture of asteroids

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