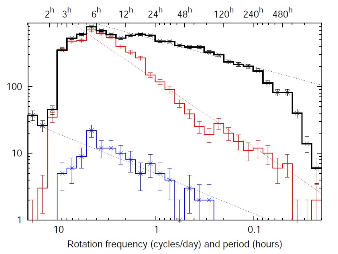
Models of long-period asteroids from simultaneous optimisation using visible and thermal data

A. Marciniak[(1)],
J. Ďurech[(2)], V. Alí-Lagoa[(3)], W. Ogłoza[(4)], R. Szakáts[(5)], T. G. Müller[(3)],
L. Molnár[(5,6,7)], A. Pál[(5,8)], F. Monteiro[(9)],
and a team of 60 observers

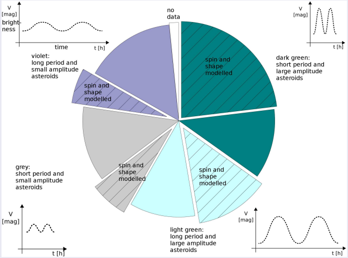
(1): Astronomical Observatory Institute, Faculty of Physics, A. Mickiewicz University, Słoneczna 36, 60-286 Poznań, Poland
e-mail: am@amu.edu.pl
(2): Astronomical Institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Prague 8, Czech Republic
(3): Max-Planck-Institut für Extraterrestrische Physik (MPE), Giessenbachstrasse 1, 85748 Garching, Germany
(4): Mt. Suhora Observatory, Pedagogical University, Podchorążych 2, 30-084, Cracow, Poland
(5): Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, Eőtvős Loránd Research Network (ELKH), H-1121 Budapest, Konkoly Thege Miklós út 15-17, Hungary
(6): MTA CSFK Lendület Near-Field Cosmology Research Group
(7): ELTE Eötvös Loránd University, Institute of Physics, 1117, Pázmány Péter sétány 1/A, Budapest, Hungary
(8): Astronomy Department, Eötvös Loránd University, Pázmány P. s. 1/A, H-1171 Budapest, Hungary
(9): Observatório Nacional, R. Gen. José Cristino, 77 - São Cristóvão, 20921-400, Rio de Janeiro - RJ, Brazil

Introduction

- Slow rotators are ubiquitous among asteroids (see recent results from Kepler K2 and TESS, Molnár et al. 2018; Pál et al. 2020)
- Ground-based lightcurve surveys disfavoured targets with P>12 hours
- Scarcity of dense lightcurves → lack of spin and shape models → biased statistics
- Also poorly studied in thermal infrared
- Particularly interesting targets for thermophysical modelling (TPM) → Larger skin depth?
- Reports of larger thermal inertia for longer rotation periods (Harris & Drube 2016; 2020)
- Lightcurve inversion shapes used in TPM: results sensitive to small-scale shape variations (Hanuš et al. 2015)



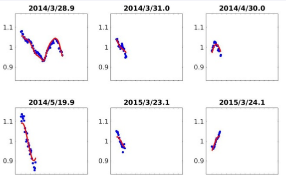
Histogram of asteroid rotation periods from ground-based observations (red), Kepler K2 (blue), and TESS (black) [from: Pál et al. 2020].



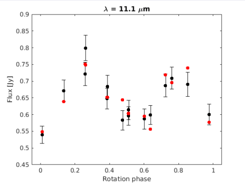
Distribution of rotation periods and amplitudes in ∼ 1200 main belt asteroids. Scarcity of spin and shape models for slow rotators, especially with small-amplitude lightcurves (violet).

Methods

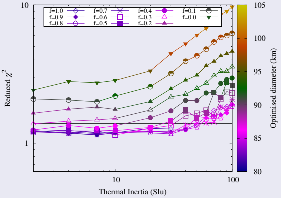
- Our photometric survey focuses on ∼100 slow rotators (Marciniak et al. 2015; 2019)
- Dense lightcurves gathered thanks to 25 small telescopes worldwide + Kepler and TESS data
- Aim: to decrease the bias, determine thermal inertia and sizes
- Thermal data from infrared satellites: WISE (Wright et al. 2010), IRAS (Neugebauer 1984), and AKARI (Usui 2011)
- A novel approach: simultaneous optimisation of visible and thermal data using Convex Inversion Thermophysical Model (CITPM, Ďurech et al. 2017)
- Result: size-scaled shape models + thermal inertia
- Good fit to both thermal and visible data



Example of model fit (red lines) to visible lightcurves (blue points) for (667) Denise.



Thermal lightcurve fit (red) to WISE W3 data (black) for (667) Denise.



Reduced χ_2 vs. thermal inertia for various combinations of surface roughness (symbols) and optimised diameters (colours). Target: (667) Denise.

Results

Sizes from CITPM are confirmed by fitting to stellar occultations (PDS, Herald et al. 2019).

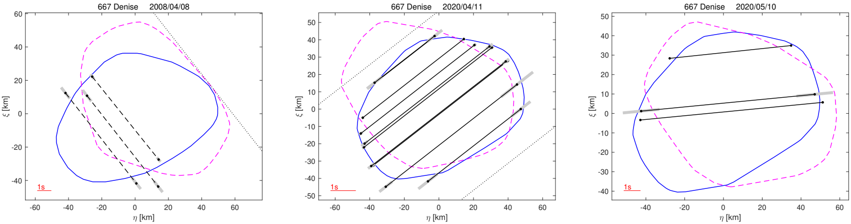


Figure: CITPM shape models of (667) Denise fitted to three stellar occultations. Pole 1 solution (blue) is clearly preferred over pole 2 (magenta). Occultation observers: R. Nugent, G. Nason, M. McCants, P. Maley, D. Weber; S. Meister, A. Schweizer, C. Ellington, S. Sposetti, A. Manna, A. Ossola, O. Schreurs, M. Bigi, P. Baruffetti, F. Van Den Abbeel, J. Bourgeois, R. Boninsegna; K. Hanna, K. Green, R. Kamin, S. Conard, K. Getrost, A. Scheck, A. Caroglanian, J. Massura, J. Harris, C. Anderson, K. Thomason, M. Wasiuta, B. Billard.

Target	CITPM		occultation scaling	
	Pole 1	Pole 2	Pole 1	Pole 2
362 Havnia	92^{+6}_{-5} km	91^{+8}_{-3} km	84 ± 1 km	88 ± 1 km
618 Elfriede	145^{+15}_{-13} km	146^{+15}_{-16} km	145 ± 7 km	155 ± 2 km
667 Denise	83^{+4}_{-2} km	82^{+5}_{-2} km	83 ± 2 km	rejected

Table: Diameters of equivalent volume spheres from CITPM and from fitting these models to stellar occultations.

All results

Asteroid	Pole		P	vis. dev	D	p_V	Γ	χ^2_{red}	r_{hel}	Γ_{1AU}
	$\lambda_p [^\circ]$	$\beta_p [^\circ]$	[hours]	[mag]	[km]		[SI units]	IR	[AU]	[SI units]
(108) Hecuba	181 ± 2	$+42 \pm 5$	14.25662 ± 0.00003	0.013	69^{+3}_{-1}	$0.24^{+0.04}_{-0.01}$	35^{+25}_{-30}	1.08	3.18 ± 0.10	85
	352 ± 1	$+39 \pm 6$	14.25662 ± 0.00003	0.012	70 ± 2	$0.24^{+0.04}_{-0.01}$	40 ± 30	1.10	3.18 ± 0.10	95
(202) Chryseis	94 ± 1	-49 ± 4	23.67025 ± 0.00006	0.012	90^{+4}_{-3}	$0.22^{+0.03}_{-0.01}$	< 180	0.35	2.96 ± 0.15	< 405
	261 ± 1	-34 ± 4	23.67028 ± 0.00004	0.012	90^{+3}_{-3}	$0.22^{+0.01}_{-0.01}$	< 180	0.36	2.96 ± 0.15	< 405
(219) Thusnelda	300 ± 10	-66 ± 10	59.7105 ± 0.0001	0.014	44^{+2}_{-4}	$0.19^{+0.04}_{-0.01}$	< 120	0.80	2.24 ± 0.42	< 220
(223) Rosa	22 ± 3	$+18 \pm 18$	20.2772 ± 0.0003	0.012	69^{+9}_{-3}	$0.033^{+0.006}_{-0.004}$	< 300	0.72	2.99 ± 0.12	< 680
	203 ± 2	$+26 \pm 15$	20.2769 ± 0.0003	0.012	70^{+6}_{-2}	$0.032^{+0.007}_{-0.003}$	< 300	0.78	2.99 ± 0.12	< 680
(362) Havnia	14 ± 2	$+33 \pm 2$	16.92665 ± 0.00003	0.017	92^{+6}_{-5}	$0.044^{+0.006}_{-0.004}$	< 180	0.80	2.64 ± 0.04	< 370
	208 ± 8	$+35 \pm 4$	16.92668 ± 0.00003	0.017	91^{+8}_{-3}	$0.046^{+0.004}_{-0.008}$	< 200	0.67	2.64 ± 0.04	< 410
(478) Tergeste	2 ± 5	-38 ± 8	16.10308 ± 0.00004	0.019	83 ± 4	$0.16^{+0.05}_{-0.01}$	2^{+45}_{-1}	0.94	3.05 ± 0.10	5
	216 ± 7	-62 ± 4	16.10312 ± 0.00004	0.016	81^{+5}_{-4}	$0.18^{+0.03}_{-0.02}$	26 ± 25	0.88	3.05 ± 0.10	60
(483) Seppina	127 ± 3	$+47 \pm 3$	12.720968 ± 0.000004	0.019	73^{+5}_{-2}	$0.16^{+0.04}_{-0.01}$	17^{+23}_{-12}	0.80	3.45 ± 0.14	45
	356 ± 4	$+60 \pm 3$	12.720977 ± 0.000002	0.019	74^{+4}_{-2}	$0.16^{+0.04}_{-0.01}$	23^{+17}_{-18}	0.83	3.45 ± 0.14	60
(501) Urhixidur	49 ± 40	$+84 \pm 12$	13.17203 ± 0.00002	0.019	77^{+5}_{-2}	$0.051^{+0.003}_{-0.008}$	4^{+35}_{-2}	0.53	3.20 ± 0.32	10
	262 ± 24	$+66 \pm 11$	13.17203 ± 0.00001	0.018	82^{+2}_{-4}	$0.050^{+0.002}_{-0.007}$	13^{+30}_{-11}	0.53	3.20 ± 0.32	31
(537) Pauly	32 ± 3	$+43 \pm 6$	16.29601 ± 0.00002	0.018	47^{+1}_{-2}	$0.26^{+0.03}_{-0.02}$	11^{+30}_{-10}	0.70	2.96 ± 0.45	25
	214 ± 4	$+60 \pm 9$	16.29597 ± 0.00001	0.018	46 ± 2	$0.25^{+0.05}_{-0.02}$	13^{+50}_{-12}	0.74	2.96 ± 0.45	29
(552) Sigelinde	8 ± 24	$+73 \pm 9$	17.14963 ± 0.00001	0.017	88^{+10}_{-5}	$0.030^{+0.011}_{-0.007}$	3^{+55}_{-2}	0.97	3.26 ± 0.09	7
	189 ± 18	$+60 \pm 17$	17.14962 ± 0.00003	0.017	91^{+7}_{-13}	$0.029^{+0.005}_{-0.007}$	2^{+55}_{-1}	1.13	3.26 ± 0.09	5
(618) Elfriede	102 ± 20	$+64 \pm 7$	14.79565 ± 0.00002	0.015	145^{+15}_{-13}	$0.047^{+0.010}_{-0.003}$	< 350	0.28	3.32 ± 0.10	< 860
	341 ± 13	$+49 \pm 6$	14.79564 ± 0.00002	0.015	146^{+15}_{-16}	$0.053^{+0.002}_{-0.009}$	< 400	0.32	3.32 ± 0.10	< 980
(666) Desdemona	10 ± 4	$+39 \pm 5$	14.60795 ± 0.00008	0.022	$28.4^{+0.9}_{-0.8}$	$0.111^{+0.007}_{-0.009}$	< 70	0.83	2.79 ± 0.34	< 150
	174 ± 3	$+36 \pm 11$	14.60796 ± 0.00003	0.022	$28.3^{+0.9}_{-1.0}$	$0.116^{+0.002}_{-0.014}$	< 100	0.77	2.79 ± 0.34	< 215
(667) Denise	15 ± 25	-83 ± 6	12.68499 ± 0.00003	0.024	83^{+4}_{-2}	0.051 ± 3	13^{+17}_{-8}	1.19	3.36 ± 0.38	32
	237 ± 3	*-23 ± 6*	*12.68497 ± 0.00003*	0.025	82^{+5}_{-2}	$0.051^{+0.002}_{-0.004}$	6^{+24}_{-1}	1.16	3.36 ± 0.38	15
(780) Armenia	144 ± 7	-44 ± 11	19.88453 ± 0.00007	0.014	98^{+2}_{-3}	$0.042^{+0.005}_{-0.003}$	< 300	0.47	3.00 ± 0.10	< 680
	293 ± 3	-23 ± 6	19.88462 ± 0.00009	0.015	102^{+3}_{-2}	0.038 ± 0.003	< 250	0.63	3.00 ± 0.10	< 570
(923) Herluga	218 ± 9	-68 ± 5	29.72820 ± 0.00002	0.022	$36.2^{+0.4}_{-1.5}$	$0.047^{+0.004}_{-0.003}$	37^{+15}_{-36}	0.92	2.73 ± 0.40	80
	334 ± 7	-52 ± 3	29.72826 ± 0.00001	0.023	$34.1^{+0.8}_{-1.0}$	$0.050^{+0.002}_{-0.003}$	14^{+35}_{-13}	0.95	2.73 ± 0.40	30
(995) Sternberga	27 ± 3	-20 ± 6	11.19511 ± 0.00012	0.019	$25.5^{+1.1}_{-1.4}$	$0.22^{+0.03}_{-0.04}$	< 100	0.85	2.73 ± 0.30	< 210
	222 ± 4	-26 ± 5	11.19512 ± 0.00008	0.019	$25.2^{+1.1}_{-0.9}$	$0.226^{+0.005}_{-0.032}$	< 120	0.84	2.73 ± 0.30	< 250

Spin parameters and thermophysical characteristics of asteroid models obtained here. Columns contain: asteroid name, J2000 ecliptic coordinates λ_p, β_p of the spin solution, with mirror pole solution in the second row, sidereal rotation period P, and the deviation of model fit to those light curves. Next part details the radiometric solution for combined data: surface-equivalent size D, geometric albedo p_V, thermal inertia Γ, and the reduced chi-square of the best-fit (χ^2_{red}). Last two columns give average heliocentric distance of thermal observations r_{hel} with standard deviation, and thermal inertia normalised to 1 AU Γ_{AU}.

Summary

- We recently obtained detailed models for 16 slow rotators (arXiv:2109.00463).
- Substantially enlarged the sample of modelled and precisely scaled slow rotators with available thermal inertia.
- Validated the approach of simultaneous fitting of infrared and visible data.
- Determined sizes are on average accurate at 5% precision level, D = 25–145 km.
- Thermal inertia reaches wide range of values, from 2 to < 400 SI units.
- No trends in thermal inertia with rotation period in the studied sample of MB asteroids.
- But: even the slowest rotators in our sample, have thermal skin depth of only a few millimetres.

References:

Ďurech, J., Delbo, M., Carry, B., Hanuš, J., & Alí-Lagoa, V. 2017, A&A, 604, A27
Hanuš, J., Delbo, M., Ďurech, J., & Alí-Lagoa, V. 2015, Icarus, 256, 101
Harris, A. W. & Drube, L. 2016, ApJ, 832, 127
Harris, A. W. & Drube, L. 2020, ApJ, 901, 140
Herald, D., Frappa, E., Gault, D., et al. 2019, Asteroid Occultations V3.0, NASA Planetary Data System
Marciniak, A., Pilcher, F., Oszkiewicz, D., et al. 2015, Planet. Space Sci., 118, 256
Marciniak, A., Alí-Lagoa, V., Müller, T. G., et al. 2019, A&A, 625, A139
Molnár, L., Pál, A., Sarneczky, K., et al. 2018, ApJS, 234, 37
Neugebauer, G., Habing, H. J., van Duinen, R., et al. 1984, ApJ, 278, L1
Pál, A., Szakáts, R., Kiss, C., et al. 2020, ApJS, 247, 26
Usui, F., Kuroda, D., Müller, T. G., et al. 2011, PASJ, 63, 1117
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868

Team of asteroid observers:
P. Arcoverde, R. Behrend, Z. Benkhaldoun, L. Bernasconi, J. Bosch, S. Brincat, L. Brunetto, M. Butkiewicz - Bąk, F. Del Freo, R. Duffard, M. Evangelista-Santana, G. Farroni, S. Fauvaud, M. Fauvaud, M. Ferrais, S. Geier, J. Golonka, J. Grice, R. Hirsch, J. Horbowicz, E. Jehin, P. Julien, Cs. Kalup, K. Kamiński, M. K. Kamińska, P. Kankiewicz, V. Kecskeméthy, D.-H. Kim, M.-J. Kim, I. Konstanciak, J. Krajewski, V. Kudak, P. Kulczak, T. Kundera, D. Lazzaro, F. Manzini, H. Medeiros, J. Michimani-Garcia, N. Morales, J. Nadolny, D. Oszkiewicz, E. Pakštiėne, M. Pawłowski, V. Perig, F. Pilcher, P. Pinel, E. Podlewska-Gaca, T. Polakis, F. Richard, T. Rodrigues, E. Rondón, R. Roy, J. J. Sanabria, T. Santana-Ros, B. Skiff, J. Skrzypek, K. Sobkowiak, E. Sonbas,G. Stachowski, J. Strajnic, P. Trela, Ł. Tychoniec, S. Urakawa, E. Verebelyi, K. Wagrez, M. Żejmo, K. Żukowski