Deliverable

H2020 COMPET-05-2015 project "Small Bodies: Near And Far (SBNAF)"

Topic: COMPET-05-2015 - Scientific exploitation of astrophysics, comets, and planetary data
Project Title: Small Bodies Near and Far (SBNAF)
Proposal No: 687378 - SBNAF - RIA
Duration: Apr 1, 2016 - Mar 31, 2019

WP	**WP6: Synergies from ground and space**
Del.No	**D6.4**
Title	**Gaia asteroid list**
Lead Beneficiary	UAM
Nature	Report
Dissemination Level	Confidential
Est. Del. Date	31 Jan 2017
Version	0.1
Date	30 Jan 2017
Lead Author	T. Santana-Ros, AO AMU, tonsan@amu.edu.pl

WP6 Synergies from ground and space
Objectives: To combine observational data from space and ground, from remote disk-integrated data and disk-resolved data from interplanetary missions to obtain (validated) high-quality model solutions for a wide range of applications: improvement of the scientific understanding, answering key questions for the reconstruction of minor body properties, calibration aspects, support for Gaia density determination, Hayabusa-2 target characterization and operational support, tools and methods for applications to large object samples.

Description of deliverable D6.4
The goal is to converge to a list of selected targets among the so-called "Gaia perturbers". These are large asteroids for which Gaia will be able to measure the tiny perturbation on the orbit of a sec-

ond smaller minor planet produced during a close encounter. From this observations, it will be able to derive their mass very precisely. Follow-up observations coordinated within SBNAF project will allow for a better 3D model determination of these selected asteroids, leading to an accurate density determination.

Description of deliverable

1. Introduction/background

Gaia will yield masses of more than one hundred asteroids from gravitational perturbations during close approaches with other minor bodies. In particular, Mouret, Hestroffer & Mignard, 2007 found that at least 42 asteroid masses will be derived with a precision better than 10% and 150 with a precision better than 50%. These precise determinations will be of utmost significance for the improvement of the dynamical modeling of the Solar System and also for our knowledge of the physics of asteroids.

From a physical point of view, the mass and size of an asteroid yields its bulk density, which accounts for the amount of matter making up the body and the space occupied by its pores and fractures. For a precise density determination, we need a shape model of the body, which includes its 3D shape, spin state and rotation axis orientation. These models are commonly obtained from relative photometric measurements. In consequence, an estimation of the body size is required in order to scale the model. The main techniques used for size determination are stellar occultations, radiometric techniques or AO imaging, as well as *in situ* exploration by spacecraft for a dozen of visited asteroids.

Once the density of the asteroid is calculated, we can compare its value with the grain density of meteorites with analogous composition. This allows to estimate the porosity, a parameter related to the collisional history of asteroids and to their internal structure (Britt et al. 2002). Interestingly, due to the very low number of existing precise density measurements, it is still unknown whether there is a relation between bulk density and the spectroscopic taxonomic class. Learning about such relation would give us information about the formation process of the Solar System (Zappala et al. 2002).

Nevertheless, mass values determined for “Gaia perturbers” will not be published until the final mission release, expected for 2020. Having this milestone in mind, we aim to fully characterize a selected set of asteroids for which Gaia observations will precisely yield the mass. In this document we describe the procedures followed to converge to a target list, as well as the observation campaigns planned to gather the data for deriving their scaled models.

2. “Gaia perturbers” full list

Taking advantage of the fact that Gaia regular observations have already started, we can now predict the observational sequence, or in other words, we already know with great precision what and when Gaia is going to observe during the next years. As a result, we can create a list of asteroids for which Gaia astrometric measurements will allow to derive their masses. Such list has been obtained from private communications with Gaia-DPAC (i.e. Daniel Hestroffer, IMCCE, Francois Mignard, OCA). To calculate this list, the method described in Mouret, Hestroffer & Mignard, 2007 was used. It is worth noting that the resulting list varies slightly from the one published, as the new calculations were done with updated parameters for the Gaia scanning law, which were still unknown by the time Mouret's paper was published.

2.1. State of the art of Gaia perturbers

The list received contains 140 large main belt asteroids. For each target and by means of data mining, we have investigated the state of the art in spin/shape modelling, photometric observations and thermal data from space. The results are summarized in the table attached in Annex I. In this table, all Gaia perturbers are listed and our current knowledge is divided into two main blocks:

Blue columns provide information about photometric observations (quality, quantity, amplitude, period) and best existing spin/shape model.

Purple columns are a compilation of the available thermal data from space telescopes IRAS, MSX, ISO, PLANCK, HERSCHEL, WISE and AKARI.

For the first block (photometry/models) the following information is provided:

<u>LIGHTCURVES</u>

A: indicates the quality of the best synodic period known for the given asteroid. The quality code is taken from LCDB “Asteroid

Lightcurve Database” (Warner, Harris & Pravec, 2009), where 3 corresponds to a secure solution, without ambiguity.
No. app. good data: is the number of apparitions for which we have lightcurves with enough quality to be used for spin/shape determination.

Amplitude Min Max (mag): provides the value of the minimum and maximum amplitude observed (in magnitude) considering all the apparitions for which we have data. These values provide direct information about the minimum elongation of the body, as well as some constraints on its possible spin solutions.

Period (h): Best known determination of the synodic period expressed in hours.

SPIN/SHAPE MODELS

B: Evaluation of solution uniqueness

a1: unique convex solution
a2: unique nonconvex solution
b1: similar convex and nonconvex solution
b2: nonconvex solution diverges from convex solution
c: two convex solutions

C: LCDB quality code of best spin axis solution

1: May be completely wrong.
2: Good determination, pole likely correct to 15-20°, but may be ambiguous with two or more solutions that are possible, or the sense of rotation is not determined.
3: Reliable determination of both spin axis direction and sense of rotation, i.e., prograde or retrograde.

D: In-house quality codes for spin axis and sidereal period solution

A: Objects with a unique spin solution, no matter the shape model
B: Objects with two solutions with a mirror-pole ambiguity, which could be ruled out with a single additional observation (thermal, adaptive optics, stellar occultation, radar...).
C: Asteroids with multiple pole solutions (observations needed for other geometries to constrain the model)
D: Asteroids with multiple spin state solutions (in particular, multiple sidereal period solutions)

E: In-house quality codes for shape models

A: Asteroids with detailed up to a small-scale shape model (high resultion models from in situ imaging)
B: Asteroids with a medium-scale shape details (a non-convex model which converges with the convex solution)
C: A first-order shape model, like a unique convex solution, based on dense lightcurves
D: A low-resolution first-order ("angular") shape model based on mainly sparse data or on limited dense data
E: A triaxial ellipsoid unique shape model

For the second block (thermal measurements), asteroids with available thermal data from space missions are marked with a X. References and data source are indicated at the bottom of the table.

3. Selection criteria for a photometric observing campaign

From the full list of 140 Gaia perturbers there are:

i. 11 asteroids with high quality shape model (medium-scale details and/or in situ observations)
ii. 22 asteroids with a first-order shape model (convex solution)
iii. 30 asteroids with a low-resolution (“angular”) shape model
iv. 3 asteroids with a triaxial ellipsoid shape model
v. 74 asteroids without shape model

We are interested in investigating Gaia perturbers as they will be a source of precise mass measurement, which is very rare in asteroid science. By knowing their shape and size, we will be able to derive their density, a crucial physical property to understand their internal composition. Thus, in order to enhance the number and quality of shape models available, we have selected 24 Gaia perturbers which fulfills the following conditions:

- We have little or no knowledge of their shape (iii, iv and v)
- We possess lightcurves of good quality gathered in at least 4 different aspects of the body
- Next two apparitions shall allow to cover at least one new viewing geometry

In the table attached, selected targets without model are marked in green, while objects with a poor quality model are marked in orange.

4. Photometric observations and shape modeling

The large majority of selected objects are bright enough to be observed with small-class telescopes. This means that the amateur astronomers community can greatly contribute to this campaign with their observations. This fits the objectives of Gaia-GOSA service[1], which was described in D3.1 – GOSA service upload (see also Santana-Ros et al. 2014). The selected targets have been already uploaded to the website as “follow-up targets” and users have started gathering data. Besides, our team also uses small and middle class telescopes in order to complete the composite lightcurves. The list of telescopes used is given below:

Telescope name	Aperture size (cm)	Location
Albox, MPC Z90	40	Almeria, Spain
Piszkés-Tető	100	Budapest, Hungary
Cerro Armazones	41, 84	Atacama, Chile
La Sagra	45	Granada, Spain
Borowiec	40	Poznan, Poland
OAdM	80	Catalonia, Spain
Sierra Nevada Observatory	100	Granada, Spain
Bosque Alegre Observatory	150	Cordoba, Argentina

When the data gathered fulfills the requirements for geometry and quality, we can proceed to solve the inversion problem in order to obtain a 3D shape model of the asteroid and its spin state. For that purpose, we use the SAGE modelling technique (Bartczak et al. 2014), which is able to derive non-convex shape solutions. Including concavities in the shape model is of special relevance in this case, as one can consider convex hull shapes as an envelope of the real shape. This means that the volume derived from a convex solution can be overestimated, resulting in a lower density determination.

Lastly, we don't plan to keep the photometric data gathered within this campaign exclusively for our team, and therefore we are willing to collaborate with other researchers which might have different approaches for solving the inversion problem.

[1] *www.gaiagosa.eu*

5. Additional observations – model scaling

From the shape model quality classification presented in section 3, we know that 33 high-quality shape models are currently available for Gaia perturbers. As shown above, our goal is to almost double this quantity. For the remaining asteroids, we will at least have the triaxial ellipsoid models from the Gaia photometric sparse data (Cellino et al. 2006, 2009).

For all these asteroids, we aim to make use of additional observations in order to obtain their size. By measuring asteroid's infrared emission, it is possible to estimate its size by means of thermophysical modeling (Delbo et al. 2015, and references therein). The Gaia perturbers list attached, contains information about thermal data available. From this list we have learned that all Gaia perturbers have at least some thermal measurement. This means that it shall be possible to derive a scaled model for all of them. However, the scaling factor uncertainty might be different in each case, as it depends on the number of thermal measurements. (more information is provided in D6.1 – Occultation vs thermal tools).

In order to test the size solutions obtained from thermal measurements, we plan to use timings obtained during stellar occultations. This technique allows for a direct estimation of the asteroid size, as well as a crude 2D snapshot, in case of multiple positive chords (see D6.1 for further details). Disk-resolved observations of asteroids by means of adaptive optics are a good alternative for a direct size measurement. Our team is involved in an accepted proposal to observe large asteroids with SPHERE/VLT instrument during the four semesters of 2017-2018. This will ensure image resolved observations for the large majority of Gaia perturbers. Another source of adaptive optics observations of large main-belt asteroids might be Adaptive Optics Lucky Imaging (AOLI) data from the 10-m GranTecan telescope.

6. Open points/future work

At this point, we have a clear view of the state of the art of Gaia perturbers. We have defined a short list for a photometric observing campaign, which is ongoing. We have learned that all Gaia pertubers have been observed with at least two infrared space telescopes.

For an additional source of size calibration, we will use stellar occultations and adaptive optics. It is therefore necessary to organize observation campaigns for the former events, which require the coordination of several observers located in different countries. For the latter technique, we will use the data gathered from SPHERE/VLT and AOLI. Thus the Gaia pertubers list provided, should be extended to include the results of both observing campaigns.

On the other hand, we aim to derive during the following months some new shape models from the Gaia perturbers short list. We will then try to scale them by means of thermophysical modeling and present the result in a referred journal.

7. References

- Bartczak, P., Michalowski, T., Santana-Ros, T. & Dudzinski, G. 2014, MNRAS, 443, 1802
- Britt, D. T., Yeomans, D., Housen, K., & Consolmagno, G. 2002, Asteroids III, (University of Arizona Press, Tucson), p. 485
- Cellino, A., Delbo, M., Zappala, V., Dell'Oro, A., Tanga, P., 2006, Adv. Space Res., 38, 9
- Cellino, A., Hestroffer, D., Tanga, P., Mottola, S., Dell'Oro, A., 2009, A&A, 506, 935
- Delbo, M., Mueller, M., Emery, J.P., Rozitis, B., Capria, M.T., 2015, Asteroids IV, University of Arizona Press, Tucson, 107-128
- Dotto, E., Barucci, M. A., Müller, T. G., Storrs, A. D., Tanga, P., 2002, Observations from Orbiting Platforms, Asteroids III, W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel (eds), University of Arizona Press, Tucson, p.219-234
- Ganga, K., 2014, Planck 2013 results. XIV. Zodiacal emission, Planck Collaboration, A&A 571, A14
- Hasegawa et al. 2013, PASJ 65, 34
- Mainzer, A. et al. 2011a, The Astrophysical Journal, 731, 1
- Mainzer, A. et al. 2011b, The Astrophysical Journal, 736, 2
- Mouret, S., Hestroffer, D., & Mignard, F. 2007, A&A, 472, 1017
- Müller et al. 2014, PASJ 66, 52
- Müller et al. 2017: Accepted to A&A
- Santana-Ros, T., Bartczak, P., Michalowski, T. & Tanga, P. 2014, EAS Publication Series, 67-68, 109
- Tedesco, E. F., Egan, M. P., Price, S. D., 2002, The MIDCOURSE SPACS EXPERIMENT Infrared Minor Planet Survey, AJ 124, 583-591
- Tedesco, E. F., Noah, P. V., Noah, M., Price, S. D., 2002, The Supplemental IRAS Minor Planet Survey, AJ 123, 1056-1085

- Usui et al. 2011, PASJ 63, 1117
- Warner, B., Harris, A. & Pravec, P. 2009, Icarus, 202, 134
- Zappala, V. & Cellino, A. 2002, EAS Publication Series, 2, 343

Asteroid	A	B	C	D	E	NO. APP. GOOD DATA	AMPLITUDE MIN MAX (mag)	PERIOD (h)	IRAS	MSX	ISO	PLANCK	HERSCHEL	WISE	AKARI
1 Ceres	3	-	3	A	A	6	0.02 0.06	9.07417	X	-	X	X	X	X	X
2 Pallas	3	b1	3	A	B	8	0.03 0.16	7.8132	X	-	X	X	X	X	X
3 Juno	3	a1	3	A	B	9	0.13 0.22	7.21	X	-	X	X	X	X	X
4 Vesta	3	-	3	A	A	15	0.08 0.19	5.342	X	-	X	X	X	X	X
6 Hebe	3	b1	3	A	B	9	0.05 0.21	7.2745	X	-	X	X	X	X	X
7 Iris	3	c	2+	B	C	9	0.04 0.29	7.139	X	-	-	-	X	X	X
8 Flora	3	c	3	B	C	4	0.03 0.11	12.865	X	-	-	X	X	X	X
9 Metis	3	b2	3	A	C	11	0.04 0.36	5.079	-	X	X	X	-	X	X
10 Hygiea	3	c	3	B	C	5	0.09 0.33	27.623	X	-	X	X	X	X	X
11 Parthenope	3	c	2	B	D	5	0.05 0.12	13.7204	X	-	-	X	-	X	X
12 Victoria	3	-	3	A	D	5	0.04 0.42	8.6599	X	-	-	X	-	X	X
13 Egeria	3	a1	2	B	C	4	0.12 0.47	7.045	X	-	X	X	-	X	X
14 Irene	3	a1	2	A	D	6	0.03 0.16	15.028	-	-	-	-	-	X	X
15 Eunomia	3	a1	3	A	C	11	0.36 0.56	6.083	X	-	-	X	-	X	X
16 Psyche	3	a1	3	A	B	15	0.03 0.42	4.196	X	-	-	X	-	X	X
19 Fortuna	3	a1	3	A	C	10	0.14 0.35	7.4432	-	-	-	-	X	X	X
20 Massalia	3	c	2	A	D?	7	0.15 0.27	8.098	X	-	X	X	X	X	X
24 Themis	3	-	3	B	A	7	0.09 0.14	8.347	-	-	-	-	X	X	X
27 Euterpe	3	a1	2	B	C	3	0.13 0.21	10.4082	-	-	-	-	-	X	X
29 Amphitrite	3	a1	3	A	C	10	0.01 0.15	5.3921	X	-	-	X	X	X	X
31 Euphrosyne	3	-	2	B	D	8	0.06 0.13	5.53	X	-	-	-	-	X	X
42 Isis	3	a1	3	A	D	6	0.14 0.35	13.59	X	-	-	-	-	X	X
48 Doris	3	-	2	B	D	4	0.17 0.36	11.89	X	-	-	-	-	X	X
51 Nemausa	3	-	-	B	D	9	0.10 0.25	7.783	X	-	-	-	-	X	X
52 Europa	3	b1	3	A	B	5	0.08 0.20	5.6304	X	-	X	X	X	X	X
54 Alexandra	3	a1	2	A	C	7	0.10 0.31	7.024	X	-	X	-	X	X	X
57 Mnemosyne	3	-	-	-	-	1	0.12 0.14	12.463	X	-	-	-	-	X	X
60 Echo	3	-	-	B	D	5	0.10 0.22	25.208	X	-	-	-	-	X	X
64 Angelina	3	a1	3	B	D	7	0.04 0.42	8.752	-	X	-	-	-	X	X
68 Leto	3	a1	2	A	D	3	0.10 0.53	14.848	X	X	-	-	-	X	X
74 Galatea	3	-	-	-	-	2	0.08 0.16	17.268	X	-	-	-	-	X	X
76 Freia	3	a1	-	B	C	6	0.05 0.33	9.973	X	-	-	-	-	X	X
87 Sylvia	3	b2	3	A	C	7	0.22 0.62	5.184	X	-	-	-	-	X	X
88 Thisbe	3	a1	3	A	C	6	0.08 .25	6.042	X	-	-	X	X	X	X
89 Julia	3	a1	3	A	D	2	0.10 0.25	11.387	X	X	-	-	-	X	X
91 Aegina	3	-	-	-	-	3	0.12 0.27	6.025	X	-	-	-	-	X	X
94 Aurora	3	a1	2	B	C	3	0.03 0.18	7.22	X	-	-	-	-	X	X

96 Aegle	3	-	-	-	-	1	0.05 0.29	13.82	X	-	-	-	-	X	X
100 Hekate	3	-	-	-	-	3	0.11 0.23	27.066	X	X	-	-	-	X	X
106 Dione	3	-	-	-	-	1	0.08	16.26	X	-	X	-	-	X	X
108 Hecuba	3	-	-	B	E	2	0.05 0.2	14.256	X	-	-	-	-	X	X
113 Amalthea	3	-	-	A	E	3	0.19 0.22	9.95	X	-	-	-	-	X	X
114 Kassandra	3	-	-	-	-	4	0.12 0.25	10.7431	X	-	X	-	-	X	X
121 Hermione	3	b1	3	A	B	5	0.04 0.70	5.55128	X	-	-	-	-	X	X
128 Nemesis	3-	-	-	-	-	2	0.08 0.10	77.81	X	X	-	X	-	X	X
129 Antigone	3	a1	3	A	C	13	0.21 0.49	4.9572	-	-	-	-	-	X	X
142 Polana	3	-	-	-	-	1	0.11	9.764	X	-	-	-	-	X	X
144 Vibilia	3	-	-	B	D	5	0.13 0.20	13.819	X	-	-	-	-	X	X
145 Adeona	3	-	-	-	-	3	0.04 0.15	15.071	X	-	-	-	-	X	X
162 Laurentia	3	a1	2	B	D	4	0.28 0.35	11.8686	X	-	-	-	-	X	X
168 Sibylla	3	-	-	-	-	1	-	47.009	X	-	-	-	-	X	X
171 Ophelia	3	-	-	B	D	3	0.14 0.46	6.66535	X	-	-	-	-	X	X
175 Andromache	3	-	-	-	-	5	0.21 0.30	8.324	X	-	-	-	-	X	X
199 Byblis	3	a1	-	B	D	2	0.05 0.15	5.2201	-	-	-	-	-	X	X
200 Dynamene	3	-	-	-	-	2	0.1	37.394	X	-	-	-	-	X	X
201 Penelope	3	a1	3	A	C	6	0.11 0.73	3.7474	X	-	-	-	-	X	X
206 Hersilia	3	-	-	-	-	3	0.08 0.20	11.122	-	X	-	-	-	X	X
209 Dido	3	-	-	A	?	4	0.11 0.33	5.7366	X	-	-	-	-	X	X
213 Lilaea	3	-	-	-	-	2	0.07 0.20	8.045	X	-	-	-	-	X	X
234 Barbara	3	-	-	A	B	5	0.16 0.28	26.4744	X	-	-	-	-	X	X
241 Germania	3	-	-	B	?	2	0.10 0.17	15.51	X	-	-	-	-	X	X
259 Aletheia	3	-	-	-	-	2	0.12	8.143	X	-	-	-	-	X	X
288 Glauke	3	-	-	-	-	3	0.36 0.9	1170	X	-	-	-	-	X	X
297 Caecilia	3	a1	-	B	D	4	0.15 0.27	4.163	X	-	-	-	-	X	X
301 Bavaria	3	-	-	-	-	1	0.25 0.31	12.253	X	-	-	-	-	X	X
308 Polyxo	3-	-	-	-	-	3	0.08 0.15	12.029	X	-	X	-	-	X	X
324 Bamberga	3	-	-	A	?	2	0.07 0.12	29.43	X	-	-	X	-	X	X
381 Myrrha	3	-	-	B	D	4	0.30 0.36	6.572	X	-	-	-	-	X	X
402 Chloe	3	-	-	B	D	4	0.07 0.37	10.664	X	-	-	-	-	X	X
409 Aspasia	3	b2	3	A	B	5	0.09 0.19	9.022	X	-	-	-	-	X	X
410 Chloris	3	-	-	-	-	2	0.28 0.33	32.5	X	-	-	-	-	X	X
423 Diotima	3	a1	3	A	C	7	0.05 0.20	4.775	X	-	-	-	X	X	X
441 Bathilde	3	a1	-	B	D	4	0.08 0.20	10.446	X	-	-	-	-	X	X
446 Aeternitas	3	a1	2	B	C	2	0.35 0.51	15.7413	X	-	-	-	-	X	X
468 Lina	3	-	-	-	-	2	0.10 0.18	16.33	X	-	-	-	-	X	X
500 Selinur	3	-	-	-	-	1	0.10 0.16	8.0111	X	-	-	-	-	X	X

511 Davida	3	a1	3	A	C	9	0.05 0.25	5.1297	X	-	X	X	X	X	X
514 Armida	3	-	-	-	-	1	0.16 0.42	21.851	X	-	-	-	-	X	X
521 Brixia	3	-	-	-	-	2	0.05 0.12	28.479	X	-	-	-	-	X	X
532 Herculina	3	a1	3	A	C	8	0.12 0.25	9.405	X	-	X	-	-	X	X
539 Pamina	3	-	-	-	-	1	0.10 0.22	13.903	X	-	-	-	-	X	X
541 Deborah	3	-	-	-	-	1	0.04 0.10	29.368	X	-	-	-	-	X	X
551 Ortrud	2	-	-	-	-	0	0.09 0.18	13.05	X	-	-	-	-	X	X
555 Norma	2+	-	-	-	-	0	0.06 0.20	19.55	X	-	-	-	-	X	X
566 Stereoskopia	3	-	-	-	-	1	0.03 0.25	12.103	X	X	-	-	-	X	X
578 Happelia	3	a1	-	A	D	3	0.11 0.16	10.061	X	-	-	-	-	X	X
636 Erika	3	-	1+	B	D	3	0.29 0.33	14.603	X	-	-	-	-	X	X
651 Antikleia	3	-	-	-	-	1	0.13 0.41	20.299	X	-	-	-	-	X	X
654 Zelinda	3	-	-	-	-	3	0.08 0.3	31.735	X	X	-	-	-	X	X
675 Ludmilla	3	c	3-	B	C	5	0.16 0.38	7.717	-	-	-	-	-	X	X
704 Interamnia	3	-	2	A	E	5	0.04 0.11	8.727	X	-	-	X	X	X	X
721 Tabora	3	-	-	-	-	3	0.19 0.30	7.982	X	-	-	-	-	X	X
739 Mandeville	2	-	-	-	-	1	0.14	11.931	X	-	-	-	-	X	X
742 Edisona	3	-	-	B	D	1	0.24 0.30	18.52	X	-	-	-	-	X	X
751 Faina	3	-	-	-	-	1	0.36	23.678	X	-	-	-	-	X	X
767 Bondia	-	-	-	-	-	0	-	-	X	-	-	-	-	X	X
774 Armor	2	-	-	-	-	0	0.11 0.34	6.7514	X	-	-	-	-	X	X
776 Berbericia	3	a1	3	A	C	6	0.08 0.26	7.668	X	-	-	-	-	X	X
781 Kartvelia	3-	-	-	-	-	1	0.16 0.28	19.04	X	-	-	-	-	X	X
861 Aida	3	-	-	-	-	1	0.32	10.95	X	-	-	-	-	X	X
880 Herba	3	-	-	-	-	2	0.13 0.21	12.266	-	-	-	-	-	X	X
885 Ulrike	3	-	-	B	D	1	0.55 0.72	4.9	X	-	-	-	-	X	X
907 Rhoda	3-	-	-	-	-	1	0.08 0.16	22.44	X	-	-	-	-	X	X
926 Imhilde	2	-	-	-	-	0	0.27	26.8	X	-	-	-	-	X	X
936 Kunigunde	3	a1	2	B	D	0	0.25	8.8	X	-	-	-	-	X	X
954 Li	3	-	-	-	-	1	0.11 0.25	7.207	X	-	-	-	-	X	X
957 Camelia	1+	-	-	-	-	0	0.3	150	X	-	-	-	-	X	X
1024 Hale	1+	-	-	-	-	0	0.1	16	X	-	-	-	-	X	X
1039 Sonneberga	2	-	-	-	-	0	0.41	34.2	X	-	-	-	-	X	X
1069 Planckia	3	-	-	-	-	2	0.14 0.42	8.665	X	-	-	-	-	X	X
1075 Helina	3-	-	-	B	D	1	0.64	44.9	X	-	-	-	-	X	X
1092 Lilium	3-	-	-	-	-	1	0.16 0.25	24.6	X	-	-	-	-	X	X
1189 Terentia	3	-	-	-	-	2	0.32 0.38	19.308	X	X	-	-	-	X	X
1197 Rhodesia	2	-	-	-	-	1	0.22 0.32	16.062	X	-	-	-	-	X	X
1210 Morosovia	3	-	-	-	-	2	0.36 0.56	15.2616	X	-	-	-	-	X	X

1237 Genevieve	2	-	-	-	-	1	0.17 0.23	16.37	X	-	-	-	-	X	X
1298 Nocturna	2	-	-	-	-	0	0.11	34.8	X	-	-	-	-	X	X
1331 Solvejg	2	-	-	-	-	1	0.42 0.44	19.29	X	-	-	-	-	X	X
1353 Maartje	3	a1	2	B	D	1	0.40 0.46	22.93	X	-	-	-	-	X	X
1427 Ruvuma	3	-	-	-	-	3	0.26 0.36	4.797	X	-	-	-	-	X	X
1469 Linzia	3	-	-	-	-	1	0.07 0.09	22.215	X	-	-	-	-	X	X
1517 Beograd	2	-	-	-	-	0	0.18 0.23	6.943	X	-	-	-	-	X	X
1569 Evita	-	-	-	-	-	-	-	-	X	-	-	-	-	X	X
1623 Vivian	3-	-	-	B	D	1	0.85	20.5209	-	-	-	-	-	X	X
1626 Sadeya	3	-	-	-	-	4	0.14 0.22	3.42	-	-	-	-	-	X	X
1633 Chimay	3	a1	2	B	D	2	0.40 0.58	6.5911	X	-	-	-	-	X	X
1679 Nevanlinna	3-	-	-	-	-	1	0.16	17.92	X	-	-	-	-	X	X
1687 Glarona	3	-	-	B	D	2	0.75	6.3	X	-	-	-	-	X	X
1692 Subbotina	3	-	-	-	-	1	0.3	9.2457	X	X	-	-	-	X	X
1771 Makover	3	-	-	-	-	1	0.25	11.26	X	-	-	-	-	X	X
1794 Finsen	2	-	-	-	-	0	0.38 0.58	12.346	X	-	-	-	-	X	X
2219 Mannucci	-	-	-	-	-	-	-	-	X	-	-	-	-	X	X
2301 Whitford	2	-	-	-	-	0	0.35 1.0	14.2751	-	-	-	-	-	X	X
2323 Zverev	3	-	-	-	-	2	0.36 0.39	3.921	-	-	-	-	-	X	X
2453 Wabash	3	-	-	-	-	1	0.63 0.67	6.878	-	-	-	-	-	X	X
2774 Tenojoki	2+	-	-	-	-	0	0.3	11.2	X	-	-	-	-	X	X
2951 Perepadin	3	-	-	-	-	3	0.54 0.60	4.781	X	-	-	-	-	X	X
3089 Oujianquan	3-	-	-	-	-	1	0.45 0.52	14.328	X	-	-	-	-	X	X
3278 Behounek	-	-	-	-	-	-	-	-	X	-	-	-	-	X	X
4003 Schumann	3-	-	-	-	-	1	0.20 0.23	5.7502	-	-	-	-	-	X	X

Enough data and...

Poor quality model

Without model

Photometry/shape models

(A) Synodic period (low precision) determination quality code from LCDB "Asteroid Lightcurve Database"
(Warner, Harris, Pravec 2009, Icarus 202, 134. Updated December 2014). "3" - secure solution, no ambiguity.

(B) Evaluation of solution uniqueness

a1: unique convex solution
a2: unique nonconvex solution
b1: similar convex and nonconvex solution
b2: nonconvex solution diverges from convex solution
c: two convex solutions

(C) Quality code of best spin axis solution (source: LCDB)
0 Later proven to be wrong.
1 May be completely wrong.
2 Good determination, pole likely correct to 15-20°, but may be ambiguous with two or more solutions that are possible, or the sense of rotation is not determined.
3 Reliable determination of both spin axis direction and sense of rotation, i.e., prograde or retrograde.

(D) Poznan team quality codes for spin axis and sidereal (high precision) period solution:
A Objects with a unique spin solution, no matter the shape model
B Objects with two solutions with a mirror-pole ambiguity, which could be ruled out with a single additional observation (thermal, adaptive optics, stellar occultation, radar...).
C Asteroids with multiple pole solutions (observations needed for other geometries to constrain the model)
D Asteroids with multiple spin state solutions (in particular, multiple sidereal period solutions)

(E) Poznan team quality codes for shape models:
A Asteroids with detailed up to a small-scale shape model (high resultion models from in situ imaging)
B Asteroids with a medium-scale shape details (a non-convex model which converges with the convex solution)
C A first-order shape model, like a unique convex solution, based on dense lightcurves
D A low-resolution first-order ("angular") shape model based on mainly sparse data or on limited dense data
E A triaxial ellipsoid unique shape model

Thermal data source

1) IRAS
Tedesco, E. F., Noah, P. V., Noah, M., Price, S. D.,
The Supplemental IRAS Minor Planet Survey,
AJ 123, 1056-1085 (2002)

2) MSX

Tedesco, E. F., Egan, M. P., Price, S. D.,
The MIDCOURSE SPACS EXPERIMENT Infrared Minor Planet Survey,
AJ 124, 583-591 (2002)

3) ISO

Dotto, E., Barucci, M. A., Müller, T. G., Storrs, A. D., Tanga, P.,
Observations from Orbiting Platforms,
Asteroids III, W. F. Bottke Jr., A. Cellino, P. Paolicchi, and
R. P. Binzel (eds), University of Arizona Press, Tucson, p.219-234 (2002)

4) Planck

Planck 2013 results. XIV. Zodiacal emission,
Planck Collaboration, A&A 571, A14 (2014);
corresponding author: K. Ganga

5) Herschel

WP4 Asteroid-related calibration:
* D4.1 Observation summary table (Section V)
* D4.3 Calibration asteroid model predictions (Release note for HSA upload)

6) WISE

The WISE/NEOWISE data were retrieved following the recommendations in Mainzer
et al. (2011a) (BC: 2011ApJ…736..100M,
link: http://iopscience.iop.org/article/10.1088/0004-637X/736/2/100).

In summary, for each asteroid we queried the Minor Planet Center (MPC) for all
detections reported by the WISE Moving Object Processing System (WMOPS,
Mainzer et al. 2011b; BC: 2011ApJ…731…53M;
link: http://iopscience.iop.org/article/10.1088/0004-637X/731/1/53).

WISE/NEOWISE detections are given the observatory code C51 in the MPC.
The output of this query is a set of time and positions for each detection,
which were used as input to the NASA/IPAC Infrared Science Archive (IRSA)
Gator search engine (http://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-scan).
We queried the four level-1b catalogues:
1. WISE All-Sky Single Exposure (L1b) Source Table
2 WISE 3-Band Cryo Single Exposure (L1b) Source Table
3. WISE Post-Cryo Single Exposure (L1b) Source Table

4. NEOWISE-R Single Exposure (L1b) Source Table.
Following Mainzer et al. (2011a), we required that the matching IRSA/IPAC
entries where 1 arc-second or closer to the MPC reported detection, and the
corresponding times of observation to be within 4 seconds.

7) AKARI
taken from: http://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/Asteroid_Flux_V1/
based on:
* Usui et al. 2011, PASJ 63, 1117: the all-sky survey
* Hasegawa et al. 2013, PASJ 65, 34: the slow-scan observations
* Mller et al. 2014, PASJ 66, 52: the pointed observation (25143 Itokawa)
* Müller et al. 2017: Accepted to A&A: the pointed observation (162173 Ryugu)