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)
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WP	**WP1 Management & Outreach**
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WP1 Management & Outreach
Objectives: To coordinate and manage the SBNAF team and the WPs in line with the objectives, milestones, and deliverables described in the proposal and in conformity with the consortium agreement (CA).

SBNAF Mid-Term Report

1. Introduction

The SBNAF public mid-term report is not part of the official requested reporting scheme of the H2020 projects, but here defined as a deliverable about 18 months after the project has started. The goal of this report is to give a short status of all WPs and deliverables, to present the results, publications, conference contributions, tools, project-specific web-pages (internal & external), but also to give an overview of the team members, expertise, contributions to the SBNAF project. The mid-term report also discusses technical & organisational problems, delays, changes with respect to the Grant Agreement statements. It also gives outreach activities and our connections to the public. There is no official financial statement connected to this report.

All relevant project information is available on the SBNAF-internal, password-protected web page: http://www.mpe.mpg.de/~tmueller/SBNAF/sbnaf.html. The public page at http://www.mpe.mpg.de/~tmueller/sbnaf advertises the project to the public and the planetary community:

2. WPs & Deliverables: Status and open points

a) WP1 Management and Coordination (Lead beneficiary: MPG)

The workload in this WP1 is significantly higher than expected, with high workload at the beginning of the project and in the context of the biannual team meetings. Most of the work is related to the communication within the team, clarification of administrative and financial aspects, maintenance of web pages (internal and public), documentation of conducted work, action items, collection of work, outreach, conference, and auxiliary material, organization and conduction of in-person, Skype, and Webex team meetings, handling of deliverables, reports, etc.
We organize regular online meetings to exchange information and discuss upcoming deliverables and ongoing science projects, as well as planning of observing proposals and observations, organization of data reduction, conference attendance, etc. These meetings take place every 2-3 weeks and the meeting minutes are made available on the SBNAF internal page. We also collect and follow up on action items on a separate page which serves also as a repository for topics, documents, emails, discussion points, etc.
The deliverables D1.1 and D1.2 were completed on time, D1.3 was delayed by about six weeks due to the close connection to our team meeting at Konkoly Observatory in October 2017.

- D1.1 Internal web page (30 Apr 2016)
- D1.2 Public web page (31 May 2016)
- D1.3 Mid-term report (planned for 15 Nov 2017)

<u>Open points & problems:</u>

- No major obstacles are expected for the second half of the project, assuming that there are no significant changes in the available manpower and contact points.
- We expect that towards the end of the project we will lose manpower since many team members are only on short-term contracts and have to find new jobs.
- Due to local procedures and AMU administration issues, the purchase and full operation of a computer cluster has been delayed.

b) WP2 Infrared observations (Lead beneficiary: MTA CSFK)

The objectives of WP2 are to produce expert-reduced Herschel data of primary focus targets: (a) large TNOs (photometric and lightcurve observations); (b) MBAs (science and calibration observations); (c) dedicated NEA observations. To collect auxiliary infrared data from previous missions (Spitzer, Planck, WISE, AKARI, IRAS, ISO, MSX) and published ground-based mid-IR, submillimetre, millimetre observations and to prepare data for integration in a unique database. To create a database of infrared observations of all SBNAF targets (TNOs, MBAs, NEAs) with the option for extension to a larger sample.
In the first 1.5 years of the project the focus was on the production of “User provided data products (UPDP)” for an upload to the Herschel Science Archive (HSA). In the second 1.5 years the emphasis is on the creation of a public database for thermal observations of asteroids.

- D2.1 Herschel tools (30 Sep 2016): A final set of tools and methods for Herschel/PACS moving target data reduction was created and made available to the Herschel Science Center (HSC) and the Planetary Science community. In parallel, we created overview lists of the various Herschel/PACS data sets for NEAs, MBAs, Centaurs, TNOs, and satellites, together with the parameters which are relevant for the data reduction (photometer observing mode, instrument and satellite settings).

- D2.2 NEA HSA upload (31 Dec 2016): All Herschel/PACS NEA observations were manually reprocessed and the photometry was extracted for various publications. The new data products were delivered to the HSC and they are meanwhile available via the HSA and also in the NASA/IPAC Infrared Science Archive. Details are described in D2.2 and in a special release note for the HSA.
- D2.3 MBA HSA upload (31 Mar 2017): The standard data reduction worked fine for most of the MBA observations. Only in very few cases we had to reprocess the data with our SSO-specific tools. The new UPDPs were delivered to the HSC and they are meanwhile available via the HSA and soon also in the NASA/IPAC Infrared Science Archive for the planetary community. Details are described in D2.3 and in a special release note for the HSA.
- D2.4 TNO HSA upload (15 Nov 2017): All Herschel/PACS TNO and Centaur observations were manually reprocessed and UPDPs were created, often from the combination of several observations to eliminate background contamination. The new UPDPs were delivered to the HSC and they will be made available via the HSA and soon also in the NASA/IPAC Infrared Science Archive. Details are described in D2.4 and in a special release notes for the HSA.
- D2.5 IR database (internal) (planned for 30 Sep 2018): We are currently setting up a prototype for a database to store thermal measurements of our SBNAF objects. We have created a first set of requirements for such a database.
- D2.6 IR database (public) (planned for 31 Mar 2019): Our goal is to have this database ready and open to the public by early 2019. This would allow to do careful testing by external experts in preparation for the workshop on "Thermal Models for Planetary Science (TherMoPS) III" which will take place in Budapest, Hungary, 20-22 Feb 2019 (organized by the SBNAF team). The IR database will also be extremely useful in the context of the JWST mission (current launch is foreseen for mid 2019).

Open points & problems:

- For our IR database, we have to understand the calibration and the quality aspects for the thermal measurements of asteroids very well in order to assign realistic error bars to each flux entry in the database. For some of the data sets (like the WISE red/blue calibrator discrepancy) we are still struggling with the correct handling of the measurements. This work also requires cross-calibration between different missions and instruments to better understand their absolute calibration schemes.
- We have started to think about a long-term availability of the WP2 results beyond the 3-year SBNAF duration: the Herschel products are available via the HSA and the NASA-/IPAC Infrared Science Archive, but for our IR database the future is not clear yet. One option would be to join the EU-funded Virtual European Solar And Planetary Access (VESPA[1]) project. VESPA aims at building a Virtual Observatory for Planetary Science, connecting all sorts of data in the field, and providing modern tools to retrieve, cross-correlate, and display data and results of scientific analyses. A first contact was established (during the EPSC conference in Sep. 2017) and VESPA requirements and guidelines were exchanged.

c) WP3 Lightcurve inversion technique (Lead beneficiary: UAM)

The goal of WP3 is to join various types of data for full physical models of benchmark asteroids and to develop web services with a database in order to provide the models to the community.

- D3.1 GOSA service upload (30 Sep 2016): The Gaia-Ground-based Observational Service for Asteroids (Gaia-GOSA, www.gaiagosa.eu) is a website contributing to the European Space Agency *Gaia* mission. It facilitates the planning of observations, the

[1] http://europlanet-vespa.eu/

gathering of lightcurves, and serves as a repository for all kind of asteroid observations. As part of D3.1 new information has been included about stellar occultation predictions for selected asteroids. GOSA observers are now also able to plan observations of these events and to coordinate between observers. Observations gathered will be exploited within SBNAF project. On the basis of these observations it will be possible to determine asteroids' size, test or improve shape model and it will also lead to new discoveries (e.g. satellites, rings or any other material orbiting the main body).

- D3.2 Prediction of shape orientations (31 Mar 2017): The predictions of shape orientations are important in the context of forecasting occultation events. Via the ISAM (Interactive Service for Asteroid Models) service upgrade it is now possible to load any of the currently about 900 shape models and to make predictions about the object's orientation at any given time. This will greatly facilitate the planning of occultation measurements and will help to verify shape/spin solutions or even to improve shape solutions. It will also allow to scale shape models from lightcurve inversion techniques which have no size assigned. This ISAM service upgrade is also important in the context of radiometric solutions and AO imaging results: details and examples are given in D3.2.
- D3.3 Shape & Spin solutions for secondary calibrators (31 Mar 2017): The main goal was to provide updated spin and shape models for around 30 large main-belt asteroids as secondary calibrators for WP4. This is a very important collection of information and data sources for these objects which will be used in the context of WP4 and WP6. The discussion for each object shows the need for more lightcurve observations in several cases. This work of collecting information for our sample will continue throughout the SBNAF project duration.
- D3.4 Volume determination (03 Nov 2017): One of the key elements is to establish reliable shape and volume determinations for large asteroids where Gaia will provide mass estimates from orbit perturbations. The critical part here is clearly the scaling of shape/spin solutions which can be done via radiometric techniques, occultation measurements, or other techniques like AO imaging, radar echo, or in-situ measurements. We describe these techniques, and introduce triaxial, convex, and non-convex shape models. We also collect critical observations for each object and demonstrate the validation of the scaling via stellar occultations and radiometric techniques. All these aspects are discussed with the goal to obtain the most realistic volumes (and errors) for large main-belt asteroids.
- D3.5 Joint lightcurve and thermal models (planned for 31 Mar 2018): The simultaneous usage of lightcurves and thermal data in the inversion process seems to be very complex, but we are working on solutions and recipes on how to test shape/spin solutions against thermal measurements.
- D3.6 Joint multi-data inversion models (planned for 31 Mar 2019): ongoing work for selected individual targets via dedicated publications (see section on recent publications).

<u>Open points & problems:</u>

- Good-quality shape models require multi-apparition high-quality lightcurves. For some targets, it is difficult to obtain enough data to find reliable shape-spin solutions. Sometimes the data have poor quality or our planned observing campaigns failed due to rejected proposals or bad weather, in other cases we will need observations during future apparitions (outside the SBNAF duration). There are also cases where the rotation period of a given object is very long (and/or the lightcurve amplitude is very small) which makes the inversion technique more difficult or even impossible.
- We know that many objects do have non-convex shapes and the reconstruction of the shape features are much more demanding and requiring more multi-apparition high-quality lightcurves than typically needed for convex inversion techniques. Also, the testing of non-convex shapes is not trivial, but can be done via AO imaging, occultations and radiometric tests. However, a final quality assignment for the non-convex solutions will be very difficult.

- We are also learning from the experience by other groups on simultaneous multi-data inversion attempts. Such exercises depend very much on how much weight is given to a specific data set and it is hard to find a balance between data from such different sources like optical lightcurves, occultation chords or AO images. Currently, we plan to work on lightcurve-based shape models, combined with scaling/validating of the solutions by using thermal data, occultation information and/or AO images.
- The calculation of non-convex shape solutions is very CPU consuming. Currently, we are limited in computer power due to budget restrictions for the refurbishment of the computer room at AMU/Poznań observatory which prevents us from the installation of the new cluster.

d) WP4 Asteroid-related calibration (Lead beneficiary: MPG)

The goal of WP4 is to improve asteroid model predictions for a transport of the space-based (Herschel, Planck, Akari) calibration to ground-based and airborne infrared, submm, and millimetre projects with a high demand for asteroids as calibrators. The prerequisites for higher-quality asteroid models for calibration applications are: (i) availability of a validated thermophysical model code to handle epoch-specific illumination and observing geometries; (ii) reliable shape/spin solutions for the large main-belt asteroids; (iii) high-quality size and albedo information; (iv) verified thermal properties; (v) characterization of the errors for specific objects and model predictions.
WP4 is closely related to the work in WP2 and WP5 (conducting and collecting of observations in the visible and infrared range), but also to WP3 (finding reliable shape and spin-vector solutions) and WP6 (combining all information in final shape-spin-size-etc. solutions for our calibration targets and characterizing the quality of the work). Another important aspect of WP4 is the identification and collection of calibration requirements of different observatories and instruments. This requires a close collaboration with the calibration teams and exchange of information and calibration products. We make all our asteroid calibration models available on our public web page at:
http://www.mpe.mpg.de/~tmueller/sbnaf/results/.

The SBNAF project supports worldwide calibration activities for ground-/airborne-/space-projects at mid-IR/far-IR/submm/mm wavelengths by providing highly reliable model predictions of selected well-known asteroids. These activities are documented in a series of deliverables which are produced as part of WP4 of the SBNAF project.
- D4.1 Observation summary table (30 Apr 2016): Provides a collection of existing and missing information & observational data (thermal IR and observations for shape and spin reconstruction) for the potential asteroid calibrators; criteria for the calibrator definition; model versions and quality category descriptions, as well as open points.
- D4.2 Submm/mm model predictions (30 Jun 2016): Provision of model v0 predictions (10-30% absolute accuracy) for 20 asteroids for period 2016-2020 mainly for calibration planning purposes. These models were delivered to the calibration teams of ALMA, APEX, IRAM, SOFIA, etc. and are available on our public web page. The deliverable includes the current best model input values like size, albedo, H-G solutions, various auxiliary information (apparent motion, phase angles, helio- and geocentric distances, background confusion and expected mm fluxes in the time period 2016-2020). We also listed the calibration contact points in the different observatories/projects and the relevant publications.
- D4.3 Calibration asteroid model predictions (30 Sep 2016): The deliverable describes the work which went into the setup for the current asteroid calibrator models (v0, v1, v2). For Ceres, Pallas, Vesta, and Lutetia we provided high-quality model (v2) solutions with high time resolution (15 min or 1 hour) at 10 reference frequencies for the period 2014-2020. In addition, we provided 1433 FITS files with thermophysical model predictions (model v1 or v2) for all 28 Herschel-PACS/SPIRE/HIFI calibration asteroids at observation mid-

time (in the "@herschel" reference frame). These predictions are meanwhile available from the Herschel Science Archive (HSA[2]) and on our public SBNAF page for the worldwide planetary community (together with a dedicated release note).

- D4.6 Selection of secondary asteroid calibrators (31 Mar 2017): In D4.6 we collected the calibration needs and requirements of ongoing and future far-IR/submm/mm projects. We also looked in more details at the available information/observations and discuss which of the large main-belt asteroids can be used as calibration standards. At the end, we established a recipe for the final selection of secondary asteroid calibrators.
- D4.4 Secondary asteroid models (planned for 31 Mar 2018): we already started to work on a final model setup for each individual (secondary) asteroid. The setup also includes a collection of thermal data, occultation data, AO images, etc. to find the best possible thermophysical solution for each asteroid (including shape/spin solution, size, albedo, thermal properties, quality description). This work goes in parallel with publications of results on subsets of this sample.
- D4.5 Final asteroid models (planned for 31 Mar 2019): At the end of the project we plan to make all final model solutions (with all model input parameters) available to the planetary community. Our findings will be published (mainly connected to physical and thermal object properties) in refereed journals with open access via the arXiv server. The scaled model solutions will be available via the ISAM service, dedicated far-IR/submm/mm predictions will be presented on the public SBNAF page and provided to the various calibration teams worldwide.

Open points & problems:

- The requirements for celestial calibration standards are often very challenging (on brightness, on absolute flux accuracy, on availability, on variability, etc.). Our final set of potential asteroid calibrators will fulfill many of the requirements, but not all.
- It is also not easy to assign reliable error bars to the asteroid model predictions, especially at submillimeter and millimeter wavelengths (or longer wavelengths) where we have only very few options to test and verify our models.
- A last point is related to requesting measurements in the context of establishing new calibrators: most of the observatories do not accept "calibration proposals" and additional observations are difficult to obtain.

e) WP5 Ground-based observations (Lead beneficiary: CSIC)

WP5 has the main goal to execute observations from ground- based telescopes with the objective to acquire more data on the targets. One type of observation is the occultation of a star by an asteroid, Centaur or TNO. On this particular point, the main tasks are to coordinate observations and produce results on physical parameters of the asteroids, Centaurs and TNOs.

- D5.1 Occultation candidates for 2016 (30 Apr 2016): In D5.1 we describe the candidates of asteroids and trans- Neptunian objects (TNOs) that could produce a stellar occultation during the year 2016 in regions where we have established networks of experienced observers (mainly Europe and South America). For the main belt asteroids, the uncertainty is smaller and the shadow path can be trusted, while for TNOs the orbits are less known with the consequence that the shadow path is only estimated and more telescopic observations (astrometry of stars and TNOs) are needed until the event is confirmed. The D5.1 predictions were produced using the free software Occult[3], together with our own refined techniques. The results on the TNOs list are unique as the IAA/Granada group is (in collaboration with the Paris-observatory group and the Rio de Janeiro group) the only team, which produces such predictions for TNOs.

[2] Herschel Science Archive (HSA) http://archives.esac.esa.int/hsa/whsa/

[3] http://www.lunar-occultations.com/iota/occult4.htm

- D5.4 High-precision photometry measurement table (30 Sep 2016): Highly reliable photometry (absolute, calibrated magnitudes) is essential for our work in WP6 where we combine data from different sources and wavelengths. Here we describe the H-G, the H-G12, and the H-G1-G2 system in the context of our targets. We explain the various aspects related to NEAs, MBAs, and TNOs. At the end, we present an overview table with the high-precision photometry results for our SBNAF targets.
- D5.2 Occultation candidates for 2017 (31 Dec 2016): Similar to D5.1, but now for the year 2017.
- D5.5 Time-series photometry measurement table (31 Mar 2017): We describe the available lightcurve data (= time-series photometry) for our project. We conduct regular observing campaigns at many intermediate-size telescopes in Spain, Hungary, Poland, Chile, Argentina, and through the Gaia-GOSA network of observers. We also use the Kepler-K2 mission to obtain high-quality, long-duration lightcurves over several days (each time we find SBNAF targets in the corresponding FOV). In addition, we started to use WISE/NEOWISE W1 data which contain in many cases sparsely sampled lightcurves (only cases where the W1 at 3.4 micron contains mainly reflected light).
- D5.6 Observational publications 1 (31 Mar 2017): A brief description of the different observational techniques used to obtain auxiliary data of the SBNAF targets and applications of all these observational data. The techniques are: 1. Time-series observations; 2. Astrometric measurements; 3. Stellar occultations; 4. Absolute photometry; 5. Thermal data. A list of works (published or in preparation) related to each observational technique within the SBNAF project is provided. This list will be updated for the subsequent deliverables: "D5.7 Observational publications 2" and "D5.8 Observational publications 3".
- D5.3 Occultation candidates for 2018 (31 Dec 2017): Similar to D5.1 and D5.2, but now for the year 2018.
- D5.7 Observational publications 2 (31 Mar 2018): see D5.6, including the recently measured occultation events for the TNO Haumea (Nature publication) and the Centaur 2002 GZ_{32} (publication in prepration).
- D5.9 Observations delivery to MPC, CDS & PDS (28 Feb 2019): ongoing
- D5.8 Observational publications 3 (31 Mar 2019): see D5.6 and D5.7

<u>Open points & problems:</u>

- Good-quality occultation shadow-path predictions (mainly for Centaurs/TNOs) require astrometric observing campaigns in the months/weeks/days before the event. And even a successful prediction does not automatically lead to successful measurements if the shadow path is in regions with bad weather or without experienced observers or over the oceans. The success rate is therefore not very high, but improved over the last years. One important element for improved predictions was the first release of GAIA data[4]. The second release (in April 2018) might again improve the situation.
- Radiometric techniques require high-precision absolute photometry (H-G values) for the determination of the object's albedo. For some targets, it is difficult to obtain enough data to find reliable H-G solutions. Sometimes the data have poor quality or our planned observing campaigns failed due to rejected proposals or bad weather, in other cases we will need observations during future apparitions (outside the SBNAF duration). This issue affects often NEAs (e.g., our Halloween-target project, see Müller et al. 2017, A&A 598, A63), but also recently discovered Centaurs and TNOs.
- Publication of observational data is typically done when significant progress in a scientific project is reached. Some of the observational data are therefore not immediately available for the Planetary Science community.

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[4] https://www.cosmos.esa.int/web/gaia/dr1

f) WP6 Synergies from ground and space (Lead beneficiary: UAM)

WP6 combines 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.

- D6.1 Occultation vs. thermal tools (31 Jan 2017): This deliverable enumerates and discusses in a unified document —which is lacking in the specialised literature— several cases relevant for our SBNAF targets in which modelling of thermal infrared/sub-millimetre data can complement stellar occultation observations in order to maximise our knowledge about those targets. There are numerous different information and data-type availability for different types of targets (NEAs, MBAs, TNOs), so this deliverable aims to provide optimal guidelines to follow in each particular case as new data are collected. In addition, it helps to demonstrate how fundamental new occultation data are for SBNAF and justifies all the efforts devoted to obtaining them in addition to visible photometry. The table in Section 3 summarises the complementary aspects of occultation versus thermal tools.
- D6.2 Shape & spin solution for primary calibrators (09 Dec 2016): This deliverable is the result of a literature survey in search for the most up-to-date and accurate three-dimensional shapes and rotational properties of our four primary calibrators (1) Ceres, (2) Pallas, (4) Vesta, and (21) Lutetia. Because they are based on ground truth information, the collection of shapes presented in the next section constitutes a significant step forward in the use of "in-situ" object properties (shape, spin-axis orientation, rotation period, size, and absolute spatial orientation at a given time) for several of the "core" objectives of the SBNAF project (these products are particularly crucial for WP4 and WP6). Table 1 contains a summary of all the information extracted and the bibliographic references where they originate.
- D6.3 In-situ object properties (31 Dec 2016): In this deliverable, we compiled in-situ physical properties of selected targets from the literature, namely visited asteroids (1) Ceres, (4) Vesta, (433) Eros and (25143) Itokawa, and flyby targets (21) Lutetia, and (951) Gaspra. We have included quantities that are not strictly in-situ properties but inferred from models, such as thermal inertias, because they are important for the SBNAF project as they are uniquely based on spatially resolved data. The deliverable includes relevant comments about each target focusing on the masses, densities, and photometric and thermal properties (whenever available). This in-situ information provides crucial ground truth to test our models, which typically deal with disc-integrated data, to assess whether these models need improvements, and to quantify how critical these are. Table 1 collects all the information and references for each target.
- D6.4 Gaia asteroid list (31 Jan 2017): The so-called "Gaia perturbers" are large asteroids for which Gaia will be able to derive the mass very precisely. This will in turn allow their density to be calculated accurately if reliable shape models are obtained. This deliverable provides a list of selected targets among the "Gaia perturbers" that have sufficiently good data coverage to grant the production of a good-quality shape model. The selection criteria and quality codes assigned to each case are explained as well. Given their relevance to the on-going photometric campaign coordinated within the SBNAF project, cases for which follow-up observations would ensure a better shape determination were identified.

- D6.5 "Ground truth" shape models (31 Mar 2017): In the first version of this deliverable we enumerated SBNAF works that were submitted for publication in which non-convex shapes of asteroids with available ground-truth information were derived. By "ground truth" we consider spacecraft-, stellar occultation- and adaptive optics-based shape models and/or constraints on shape. The works submitted for publication included e.g. (433) Eros and (9) Metis (ground truth: space mission shape and rich set of occultation chords, respectively), (6) Hebe (ground truth: adaptive optics and occultations).
- D6.5 "Ground truth" shape models (Version 2) (updated on 29 Sep 2017): In the revised version, the status of all works featured in the first version changed from submitted to accepted or published in peer-reviewed journals, which allows the inclusion of details of the contents of these articles in this public deliverable. We highlight here the article by Bartczak & Dudziński, which was accepted for publication in Monthly Notices of the Royal Astronomical Society in September 2017, as of particular relevance to the SBNAF Milestone 2. It studied the "genetic evolution" algorithm SAGE to derive non-convex shapes and validated the shape models obtained for (433) Eros and (9) Metis with the rich ground truth information available for these targets. This work also included extensive simulations to reconstruct artificial shape models.
- D6.6 Thermally resolved shape models (30 Sep 2017): This deliverable illustrates the use of thermo-physical models (TPM) to rule out mirror shape solutions derived from lightcurve inversion techniques that fit the visible data statistically equally well. A large part of the work carried out was collected in the article by Marciniak et al. (accepted for publication in Astronomy & Astrophysics in Sept. 2017; attached in Appendix A). In the deliverable, we examine more closely the TIR data coverage of the targets featured in the paper and we expand the discussion in an attempt to understand the strengths and limitations of the approach more systematically. The aim is to identify what cases are best for benchmarking, calibration (work package WP4), and/or scientific exploitation in terms of visible, TIR, mm and sub-mm data, and quantify how the TPM and TIR information can be phased in the development of a system to assess the quality of shape models (deliverable D6.7).
- D6.7 Quality assessment system for the models (31 Mar 2018): ongoing
- D6.8 3D shape models for large MBAs (30 Sep 2018): planned.

<u>Open points & problems:</u>

- When combining data from very different sources and techniques it is not trivial to assign the correct weight to each data point and data type.
- There is also no general unique procedure for combining data from ground and space. It often depends on the final scientific goal of a given project. For WP4 we try to make the best possible thermal model predictions for calibration purposes (the reliability of the model input parameters like size, thermal inertia, etc. is only of secondary importance). For the list of Gaia mass targets, the main goal is to determine the objects' sizes. Here, it is essential to derive the best-possible volumes for the targets and the scaling of the shape model is crucial. But what is the best method to scale shape models? Occultations? Radiometric techniques? AO imaging? Or a combination of all?
- There are more areas where a good model solution is not automatically a physical representation of a given object: A high-quality shape-spin solution might fit all available lightcurves within the error bars, but might have problems to match occultation information, the AO images or the available thermal data. For some targets, there are indications of colour and/or albedo variations (and maybe also variations of the scattering properties) on the surface. The inversion techniques and radiometric techniques are then less reliable.

3. Milestones

Here, we list the first four milestones which have due dates in the first 1.5 years of the project duration (as given in the Grand Agreement).

Milestone number	Milestone title	WP number	Lead beneficiary	Due Date (in months)	Means of verification
MS1	Kick-off	WP1, WP2, WP3, WP4, WP5	1 - MPG	1	In-person kick-off meeting with all participants. Means of verification: Consortium agreements, communication links, project structure, schedules, SBNAF web page
MS2	Benchmark study	WP3, WP6	4 - UAM	12	Finalization of a study on convex and non-convex shape models (including thermal measurements) for objects with ground-truth information. Means of verification: Presentation in a major conference. Publication of results in scientific journal.
MS3	Expert-reduced data to HSA	WP2	3 - MTA CSFK	18	Finalisation of expert- reduced data upload to the Herschel Science Archive. Means of verification: Availability of data in the HSA to the planetary community.
MS4	Mid-term review	WP1, WP2, WP3, WP4, WP5, WP6	1 - MPG	18	SBNAF scientific mid- term review. Means of verification: Review of the project involving external experts.

MS1 was reached by holding the SBNAF kick-off meeting at IAA/Granada, Spain, from April 13 – 15, 2016 (see picture below). All presentations, notes, and the minutes are available on the project-internal page at:
http://www.mpe.mpg.de/~tmueller/SBNAF/GRANADA2016/granada2016.html

MS2 is related to a "benchmark study" on convex and non-convex shape models (including thermal measurements) for objects with ground-truth information. We discuss this point extensively in the version2 of D6.5 where we present shape models from both convex and non-convex inversion vs. ground truth. In a first paper by Bartczak & Dudziński, MNRAS, accepted in Sep 2017, the "ground truth" comparison between lightcurve-inversion spin/shapes solutions and in-situ findings is discussed for (433) Eros and (9) Metis. In a second paper by Marciniak et al., A&A, accepted in Sep 2017 we used thermal measurements (i) to assign size, albedo and thermal inertia to

several long-period asteroids; (ii) to test convex and non-convex shape solutions; (iii) to collect experience about the pros and cons of using thermal data in the context of deriving the key physical and thermal properties for a given object. A third publication by Marsset et al. 2017, A&A 604, A64, we combine information from AO imaging, occultations, lightcurve inversion techniques, and thermal radiometry to inter-compare the results from the different techniques and to obtain the best possible solution for this large main-belt asteroid. In addition to the three papers, we also presented these projects in various international conferences. With these publications and presentations, we have reached MS2. However, we consider the entire SBNAF project as a kind of "benchmark study" to test and validate different techniques and models in the context of finding the best-possible physical and thermal properties for small bodies. Thus, work relevant for this milestone will continue until the end of the project.

MS3 is reached via D2.1, D2.2, D2.3, and D2.4. All Herschel/PACS NEA, MBAs, TNO and Centaur observations were manually reprocessed and UPDPs were created and delivered to the HSC. They are meanwhile (or will be) available via the HSA and soon also in the NASA/IPAC Infrared Science Archive for the planetary community. Details are described in the listed 4 deliverables and in special release notes for the HSA.

MS4 is reached via the finalization of this mid-term report (D1.3). Our "mid-term" team meeting was held at Konkoly Observatory in Budapest, Hungary, from Oct. 4-6, 2017. We included several external experts (i) to learn about recent developments in different fields of measuring small body properties; (ii) to provide feedback to our SBNAF work. Their presentations and feedback, as well as the discussion points are collected in the meeting minutes and notes. In addition, we are in regular contacts with other groups in the world to discuss the best strategies in lightcurve inversion techniques, radiometric modelling, advances in occultation measurements and prediction strategies. We also follow closely the results from AO imaging campaigns, and study new observing options via ground-, airborne-, and space observatories, and at new wavelength regimes (like radio frequencies). In the calibration context (WP4) we are working in close collaboration with the various stakeholders to adopt our work to new calibration requirements. We also obtain very useful feedback via the refereeing process for our scientific work (more than 30 peer-reviewed publications so far). The SBNAF project work and strategy improved significantly via the feedback from our external project referee during the Poznań team meeting (May 4-6, 2017) and his expert report, as well as the EU assessment report in the context of our first periodic report (Apr 2016 – Mar 2017).

4. Scientific results

The SBNAF scientific results are published in open access. The project itself and most of the science topics are also presented in many conferences and workshops. Here, we give a summary for the first 1.5 years of the SBNAF project.

a) Publications

The SBNAF project and the results of our work (and SBNAF contributions to other projects) are published in open access journals or on arXiv (Astrophysics). We list all publications with the SBNAF-specific acknowledgement, a few of these papers have only minor SBNAF contributions. During the first 18 months of the SBNAF project, we produced on average about one peer-reviewed publication per month with a major SBNAF contribution. Currently, we counted more than 30 publications which contain the SBNAF acknowledgement: "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."

- **Submitted:**
  - Herschel-PACS photometry of faint stars for sensitivity performance assessment and establishment of faint FIR prime photometric standards, Klaas et al., submitted in August to A&A
  - The AKARI IRC Asteroid Flux Catalogue: updated diameters and albedos, Ali-Lagoa et al., submitted in August 2017 to A&A
  - Surface ice and Tholins on the extreme Centaur 2012 DR30, Szabo, Kiss, Pinilla-Alonso et al., submitted June 2017
  - Main-belt asteroids in the K2 Uranus field, Molnár et al., submitted in June 2017 to ApJS
  - Thermophysical modelling of main-belt asteroids from WISE thermal data, Hanuš et al., submitted in August 2017 to Icarus
  - Thermal Infrared and Optical Photometry of Asteroidal Comet C/2002 CE10, by Sekiguchi et al., re-submitted to Icarus
  - In-space utilisation of asteroids (ASIME 2016 White Paper), Graps et al. 2016
- **Accepted:**
  - PRIMASS visits the Hilda and Cybele groups, De Prá, et al., accepted by Icarus in Nov. 2017
  - Small Bodies Near and Far (SBNAF): a benchmark study on physical and thermal properties of small bodies in the Solar System, Müller et al. 2017, accepted by Advances in Space Research in October 2017
  - Shaping Asteroid models with Genetic Evolution (SAGE), P. Bartczak & G. Dudziński, accepted by MNRAS in September 2017
  - The thermal emission of Centaurs and Trans-Neptunian objects at millimeter wavelengths from ALMA observations, Lellouch et al., accepted by A&A in September 2017
  - "TNOs are Cool": A survey of the trans-Neptunian region. XIII. Characterization of multiple trans-Neptunian objects observed with Herschel Space Observatory, by Kovalenko et al., accepted by A&A in September 2017
  - Photometric survey, modelling, and scaling of long-period and low-amplitude asteroids, Marciniak et al., accepted by A&A in September 2017
  - The structure of Chariklo's rings from stellar occultations, D. Berard et al., accepted by A&A in August 2017
  - Size and shape of Chariklo and its rings reflectivity from multi-epoch stellar occultations, R. Leiva et al., accepted by A&A in August 2017
- **Published:**
  - 01/2018: Spin states of asteroids in the Eos collisional family, J. Hanuš, M. Delbo', V. Alí-Lagoa, B. Bolin, R. Jedicke, J. Ďurech, H. Cibulková, P. Pravec, P. Kušnirá, R. Behrend, F. Marchis, P. Antonini, L. Arnold, M. Audejean, M. Bachschmidt, L. Bernasconi, L. Brunetto, S. Casulli, R. Dymock, N. Esseiva, M. Esteban, O. Gerteis, H. de Groot, H. Gully, H. Hamanowa, H. Hamanowa, P. Krafft, M. Lehký, F. Manzini, J. Michelet, E. Morelle, J. Oey, F. Pilcher, F. Reignier, R. Roy, P.A. Salom, B.D. Warner, Icarus 299, 84H (2018)
  - 10/2017: **The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation, Ortiz et al. 2017, Nature 550, 219-223**
  - 10/2017: A new non-convex model of the binary asteroid (809) Lundia obtained with the SAGE modelling technique, Bartczak, P.; Kryszczyńska, A.; Dudziński, G.; Polińska, M.; Colas, F.; Vachier, F.; Marciniak, A.; Pollock, J.; Apostolovska, G.; Santana-Ros, T.; and 5 coauthors, MNRAS, 471, 941

- 09/2017: Properties of the irregular satellite system around Uranus inferred from K2, Herschel and Spitzer observations, Farkas-Takács, A.; Kiss, Cs.; Pál, A.; Molnár, L.; Szabó, Gy. M.; Hanyecz, O.; Sárneczky, K.; Szabó, R.; Marton, G.; Mommert, M.; Szakáts, R.; Müller, T.; Kiss, L. L., AJ, 154, 119 (2017)
- 09/2017: Statistical analysis of the ambiguities in the asteroid period determinations, Butkiewicz-Bąk, M., Kwiatkowski, T.; Bartczak, P.; Dudziński, G.; Marciniak, A., MNRAS, 470, 1314 (2017)
- 08/2017: The EURONEAR Lightcurve Survey of Near Earth Asteroids, Vaduvescu, O.; Macias, A. Aznar; Tudor, V.; Predatu, M.; Galád, A.; Gajdoš, S.; Világi, J.; Stevance, H. F.; Errmann, R.; Unda-Sanzana, E.; Char, F.; Peixinho, N.; Popescu, M.; Sonka, A.; Cornea, R.; Suciu, O.; Toma, R.; Santos-Sanz, P.; Sota, A.; Licandro, J.; Serra-Ricart, M.; Morate, D.; Mocnik, T.; Alfaro, M. Diaz; Lopez-Martinez, F.; McCormac, J.; Humphries, N., EM&P, 120, 41 (2017)
- 08/2017: "TNOs are Cool": A survey of the trans-Neptunian region. XII. Thermal light curves of Haumea, 2003 VS2 and 2003 AZ84 with Herschel/PACS", P. Santos-Sanz, E. Lellouch, O. Groussin, P. Lacerda, T. G. Müller, J. L. Ortiz, C. Kiss, E. Vilenius, J. Stansberry, R. Duffard, S. Fornasier, L. Jorda, A. Thirouin, A&A, 604, A95 (2017)
- 08/2017: 3-D shape of asteroid (6) Hebe from VLT/SPHERE imaging: Implications for the origin of ordinary H chondrites, Marsset, M.; Carry, B.; Dumas, C.; Hanus, J.; Viikinkoski, M.; Vernazza, P.; Müller, T. G.; Delbo, M.; Jehin, E.; Gillon, M.; Grice, J.; Yang, B.; Fusco, T.; Berthier, J.; Sonnett, S.; Kugel, F.; Caron, J.; Behrend, R., A&A, 604, A64
- 07/2017: Study of the Plutino Object (208996) 2003 AZ84 from Stellar Occultations: Size, Shape, and Topographic Features, Dias-Oliveira, A., Sicardy, B., Ortiz, J. L., Braga-Ribas, F., Leiva, R., Vieira-Martins, R., Benedetti-Rossi, G., Camargo, J. I. B., Assafin, M., Gomes-Júnior, A. R., and 53 coauthors, AJ 154, 22D (2017)
- 07/2017: Asteroid shapes and thermal properties from combined optical and mid-infrared photometry inversion, Ďurech, J., Delbo', M., Carry, B.; Hanuš, J.; Alí-Lagoa, V., A&A 604, 27D (2017)
- 07/2017: Sizes and albedos of Mars-crossing asteroids from WISE/NEOWISE data, Alí-Lagoa, V., Delbo', M., A&A 603, 55A (2017)
- 07/2017: Thermal Infrared Imaging Experiments of C-Type Asteroid 162173 Ryugu on Hayabusa2, T. Okada, T. Fukuhara, S. Tanaka, M. Taguchi, T. Imamura, T. Arai, H. Senshu, Y. Ogawa, H. Demura, K. Kitazato, R. Nakamura, T. Kouyama, T. Sekiguchi, S. Hasegawa, T. Matsunaga, T. Wada, J. Takita, N. Sakatani, Y. Horikawa, K. Endo, J. Helbert, T. G. M¨ller, A. Hagermann, Space Science Reviews 208, 255-286 (2017)
- 06/2017: Assessment of different formation scenarios for the ring system of (10199) Chariklo, Melita, M. D., Duffard, R., Ortiz, J. L. and Campo-Bagatin, A. A&A 602, A27 (2017)
- 05/2017: Shape and spin distributions of asteroid populations from brightness variation estimates and large databases, H. Nortunen, M. Kaasalainen, J. Ďurech, H. Cibulková, V. Alí-Lagoa, J. Hanuš, A&A 601, A139 (2017)
- 04/2017: Physical properties of centaur (54598) Bienor from photometry, Fernández-Valenzuela, E.; Ortiz, J. L.; Duffard, R.; Morales, N.; Santos-Sanz, P., 2017, MNRAS 466, 4147F
- 03/2017: Results from a triple chord stellar occultation and far-infrared photometry of the trans-Neptunian object (229762) 2007 UK126, Schindler, K.; Wolf, J.; Bardecker, J.; Olsen, A.; Müller, T.; Kiss, C.; Ortiz, J. L.; Braga-Ribas, F.; Camargo, J. I. B.; Herald, D.; Krabbe, A. 2017, A&A 600, A12

- 03/2017: Discovery of a satellite of the large trans-Neptunian object (225088) 2007 OR10, Kiss, Csaba; Marton, Gábor; Farkas-Takács, Anikó; Stansberry, John; Müller, Thomas; Vinkó, József; Balog, Zoltán; Ortiz, Jose-Luis; Pál, András, 2017, ApJL 838, L1
- 03/2017: Hayabusa-2 Mission Target Asteroid 162173 Ryugu (1999 JU3): Searching for the Object's Spin-Axis Orientation, Müller, T. G.; Ďurech, J.; Ishiguro, M.; Mueller, M.; Krühler, T.; Yang, H.; Kim, M.-J.; O'Rourke, L.; Usui, F.; Kiss, C.; and 20 coauthors, 2017, A&A 599, A103
- 02/2017: Spectral and rotational properties of near-Earth asteroid (162173) Ryugu, target of the Hayabusa-2 sample return mission, Perna, D.; Barucci, M. A.; Ishiguro, M.; Alvarez-Candal, A.; Kuroda, D.; Yoshikawa, M.; Kim, M.-J.; Fornasier, S.; Hasegawa, S.; Roh, D.-G.; Müller, T. G.; Kim, Y., 2017, A&A 599, L1
- 02/2017: Large Halloween Asteroid at Lunar Distance, Müller, T. G.; Marciniak, A.; Butkiewicz-Bąk, M.; Duffard, R.; Oszkiewicz, D.; Käufl, H. U.; Szakáts, R.; Santana-Ros, T.; Kiss, C.; Santos-Sanz, P., 2017, A&A 598, A63
- 02/2017: The heart of the swarm: K2 photometry and rotational characteristics of 56 Jovian Trojan asteroids, Szabó, Gy. M.; Pál, A.; Kiss, Cs.; Kiss, L. L.; Molnár, L.; Hanyecz, O.; Plachy, E.; Sárneczky, K.; Szabó, R., 2017, A&A 599, 44
- 00/2017: Shape Models and Physical Properties of Asteroids, Santana-Ros, T.; Dudziński, G.; Bartczak, P., 2017, Assessment and Mitigation of Asteroid Impact Hazards, Astrophysics and Space Science Proceedings, Volume 46. ISBN 978-3-319-46178-6. Springer International Publishing Switzerland, 2017, p. 55
- 12/2016: Results from the 2014 November 15th multi-chord stellar occultation by the TNO (229762) 2007 UK126, Benedetti-Rossi, G.; Sicardy, B.; Buie, M. W.; Ortiz, J. L.; Vieira-Martins, R.; Keller, J. M.; Braga-Ribas, F.; Camargo, J. I. B.; Assafin, M.; Morales, N.; and 19 coauthors, 2016, AJ 152, 156
- 11/2016: Uninterrupted optical light curves of main-belt asteroids from the K2 Mission, Szabó, R.; Pál, A.; Sárneczky, K.; Szabó, Gy. M.; Molnár, L.; Kiss, L. L.; Hanyecz, O.; Plachy, E.; Kiss, Cs., 2016, A&A 596, 40

- **Produced during the SBNAF preparation phase (after EU approval of SBNAF project):**
  - 07/2016: Near-Earth asteroid (3200) Phaethon: Characterization of its orbit, spin state, and thermophysical parameters, Hanuš, J.; Delbo', M.; Vokrouhlický, D.; Pravec, P.; Emery, J. P.; Alí-Lagoa, V.; Bolin, B.; Devogèle, M.; Dyvig, R.; Galád, A.; Jedicke, R.; Kornoš, L.; Kušnirák, P.; Licandro, J.; Reddy, V.; Rivet, J.-P.; Világi, J.; Warner, B. D., A&A 592, 34H
  - 05/2016: Large Size and Slow Rotation of the Trans-Neptunian Object (225088) 2007 OR10 Discovered from Herschel and K2 Observations, Pál, András; Kiss, Csaba; Müller, Thomas G.; Molnár, László; Szabó, Róbert; Szabó, Gyula M.; Sárneczky, Krisztián; Kiss, László L., 2016, AJ 151, 117
  - 04/2016: The long-wavelength thermal emission of the Pluto-Charon system from Herschel observations. Evidence for emissivity effects, Lellouch, E.; Santos-Sanz, P.; Fornasier, S.; Lim, T.; Stansberry, J.; Vilenius, E.; Kiss, Cs.; Müller, T.; Marton, G.; Protopapa, S.; and 2 coauthors, 2016, A&A 588, 2L
  - 04/2016: Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations, Kiss, C.; Pál, A.; Farkas-Takács, A. I.; Szabó, G. M.; Szabó, R.; Kiss, L. L.; Molnár, L.; Sárneczky, K.; Müller, T. G.; Mommert, M.; Stansberry, J., 2016, MNRAS 457, 2908

- 04/2016: Far-infrared photometric observations of the outer planets and satellites with Herschel-PACS, Müller, T. G.; Balog, Z.; Nielbock, M.; Moreno, R.; Klaas, U.; Moór, A.; Linz, H.; Feuchtgruber, H., 2016, A&A 588, 109M
- 03/2016: 2008 OG19: a highly elongated Trans-Neptunian object, Fernández-Valenzuela, E.; Ortiz, J. L.; Duffard, R.; Santos-Sanz, P.; Morales, N., 2016, MNRAS 456, 2354
- 02/2016: Absolute magnitudes and phase coefficients of trans-Neptunian objects, Alvarez-Candal, A.; Pinilla-Alonso, N.; Ortiz, J. L.; Duffard, R.; Morales, N.; Santos-Sanz, P.; Thirouin, A.; Silva, J. S., 2016, A&A 586, 155A
- 02/2016: New and updated convex shape models of asteroids based on optical data from a large collaboration network, Hanuš, J.; Ďurech, J.; Oszkiewicz, D. A.; Behrend, R.; Carry, B.; Delbo, M.; Adam, O.; Afonina, V.; Anquetin, R.; Antonini, P.; and 159 coauthors; 2016, A&A 586, 108H
- 01/2016: GTC/CanariCam observations of (99942) Apophis, Licandro, J.; Müller, T.; Alvarez, C.; Alí-Lagoa, V.; Delbo, M., 2016, A&A 585, 10L
- 01/2016: Physical Characterization of TNOs with the James Webb Space Telescope, Parker, Alex; Pinilla-Alonso, Noemi; Santos-Sanz, Pablo; Stansberry, John; Alvarez-Candal, Alvaro; Bannister, Michele; Benecchi, Susan; Cook, Jason; Fraser, Wesley; Grundy, Will; and 6 coauthors, 2016, PASP 128, 8010
- 01/2016: James Webb Space Telescope Observations of Stellar Occultations by Solar System Bodies and Rings, Santos-Sanz, P.; French, R. G.; Pinilla-Alonso, N.; Stansberry, J.; Lin, Z.-Y.; Zhang, Z.-W.; Vilenius, E.; Müller, Th.; Ortiz, J. L.; Braga-Ribas, F.; and 7 coauthors, 2016, PASP 128, 8011S
- 12/2015: Orbit determination of trans-Neptunian objects and Centaurs for the prediction of stellar occultations, Desmars, J.; Camargo, J. I. B.; Braga-Ribas, F.; Vieira-Martins, R.; Assafin, M.; Vachier, F.; Colas, F.; Ortiz, J. L.; Duffard, R.; Morales, N.; and 3 coauthors, 2015, A&A 584, 96D
- 12/2015: Against the biases in spins and shapes of asteroids, Marciniak, A.; Pilcher, F.; Oszkiewicz, D.; Santana-Ros, T.; Urakawa, S.; Fauvaud, S.; Kankiewicz, P.; Tychoniec, Ł.; Fauvaud, M.; Hirsch, R.; and 14 coauthors, 2015; P&SS 118, 256
- 11/2015: Physical properties of the extreme Centaur and super-comet candidate 2013 AZ60, Pál, A; Kiss, Cs.; Horner, J.; Szakáts, R.; Vilenius, E.; Müller, Th. G.; Acosta-Pulido, J.; Licandro, J.; Cabrera-Lavers, A.; Sárneczky, K.; and 5 coauthors, 2015, A&A 583, 93P
- 11/2015: A method to search for large-scale concavities in asteroid shape models, Devogèle, M.; Rivet, J. P.; Tanga, P.; Bendjoya, Ph.; Surdej, J.; Bartczak, P.; Hanuš, J., 2015, MNRAS 453, 2232

b) Conferences and workshop contributions

Our SBNAF project and the results of our work are presented in many national and international conferences and workshops. Here is a list of SBNAF contributions (from large international conferences) which have available abstracts in ADS[5] (the presenting authors, the links and pdf documents are available on our SBNAF web pages):

- The 4th Workshop on Binaries in the Solar System, Prague, Czech Republic, 2016 June 21-23
    - Binaries in the Trans-Neptunian population (EFV)

[5] http://adsabs.harvard.edu/abstract_service.html

    - Update on SAGE algorithm: uncertainty maps for asteroid shape and pole solutions (GD)
- 41st Scientific Assembly of the Committee on Space Research, COSPAR 2016, Istanbul, Turkey, 30 Jul - 7 Aug 2016
    - Abstract: Small bodies: Near and Far (SBNAF) (TM)
- DPS-EPSC Joint Meeting 2016, Pasadena, CA, United States, 16-21 October 2016
    - Small Bodies: Near and Far (SBNAF) (RD)
    - Physical characteristics of Centaurs and trans-Neptunian objects from combined K2 and Herschel observations (CK)
    - Asteroid spin and shape modelling using two lightcurve inversion methods (AM)
    - Gaia-GOSA: An interactive service for coordination of asteroid observation campaigns (TSR)
    - Properties of resonant trans-Neptunian objects based on Herschel Space Observatory data (ATF)
    - Uncertainty maps for asteroid shape and pole solutions (PB)
    - Shaping Asteroid with Genetic Evolution (SAGE) using lightcurve and radar data (GD)
    - K2 and Herschel/PACS photometry of irregular satellites (AP)
    - The moon of the large Kuiper-belt object 2007 OR10 (GM)
    - Photometry of Main Belt and Trojan asteroids with K2 (GS)
    - Thermal inertia as an indicator of rockiness variegation on near-Earth asteroid surfaces (VAL)
- Asteroids, Comets, Meteors 2017, Montevideo, Uruguay, April 10-14, 2017
    - Physical properties of TNOs and Centaurs from stellar occultations and thermal observations (PSS invited talk)
    - What is Bienor hiding in its photometric behaviour? (EFV)
    - Measuring sense of rotation of V-type asteroids outside the Vesta family (DO)
    - Shape uncertainty of asteroid models from inversion techniques (PB)
    - Ryugu: 15 months to showdown (TM)
    - Updated asteroid diameters and albedos from AKARI/IRC mid-infrared data (VAL)
    - Photometry of asteroids in crowded star fields in SBNAF project (MBB)
    - Results from stellar occultations by trans-Neptunian object (84922) 2003 VS2 (PSS)
    - 2008 OG19: A Varuna-like trans-Neptunian object? (EFV)
    - Debiasing asteroid spins and shapes - observations, modeling, and validation (AM)
    - Asteroid shape reconstruction from radar echo images (GD)
    - First Results from "Small Bodies Near and Far (SBNAF)": A benchmark study for the characterization of asteroids and TNOs (TM)
- 12th European Planetary Science Congress (EPSC), 17–22 September 2017, Riga, Latvia
    - Session SB12: Small Bodies Near and Far; Convener: T. Müller; Co-convener: P. Santos-Sanz
    - The 2017 January 21st multi-chord stellar occultation by the dwarf planet Haumea. Preliminary results (JLO/PSS)
    - Physical characterization of Kuiper belt objects from stellar occultations and thermal measurements (PSS keynote talk)
    - Herschel-PACS high-precision FIR fluxes of NEAs and MBAs (TM)
    - Small Bodies Near and Far (SBNAF): Characterization of asteroids and TNOs (TM)
    - Thermal emission of the Eris-Dysnomia system (CK)

    - K2 and Herschel/PACS light curve of the Centaur 2060 Chiron (GM)
    - Serendipitous observations of asteroids in Herschel PACS and SPIRE maps (RS)
    - Asteroid phase-curves from Gaia-calibrated data (DO)
- 49th Annual Division for Planetary Sciences Meeting, 15-20 October 2017, Provo, Utah
    - The stellar occultation by the dwarf planet Haumea (PSS)
    - Dynamics of rings around elongated bodies (PSS, JLO, RD)
    - Absolute colors and phase coefficients of Trans-Neptunian objects: HV - HR colors (JLO, RD, EFV, PSS, NM)
    - The thermal emission of Centaurs and Trans-Neptunian objects at submm wavelengths from ALMA observations (TM, PSS)
    - Spatially resolved thermal emission of the Eris-Dysnomia system (CK)
    - Search for signatures of extended emission around dwarf planets on Hubble Space Telescope archival images (GM)

In addition, we attended many more workshops, national and international conferences with SBNAF-related contributions. We organized or co-organized workshops on SBNAF topics as SOC/LOC members (e.g., a specific SBNAF session in the EPSC2017 conference in Riga/Latvia, see above).

Outlook:
For the second half of the SBNAF project, we plan to attend various workshops, national and international conferences related to small bodies (for an updated list of workshops and conferences: see our internal and public web pages). In addition, we will organize the workshop "TherMoPS (Thermal Models for Planetary Science) III" in Budapest, Hungary, Feb 20-22, 2019, following up on TherMoPS I (Beaulieu sur Mer, France, Sep 15-17, 2008) and TherMoPS II (Puerto de la Cruz, Tenerife, Spain, Jun 3-5, 2015). We expect that about 50-100 experts in the field of small bodies will participate in this workshop, including members of the Rosetta, the New Horizons, the Hayabusa-2, the OSIRIS-Rex teams, as well as experts in observations and modelling of small bodies.

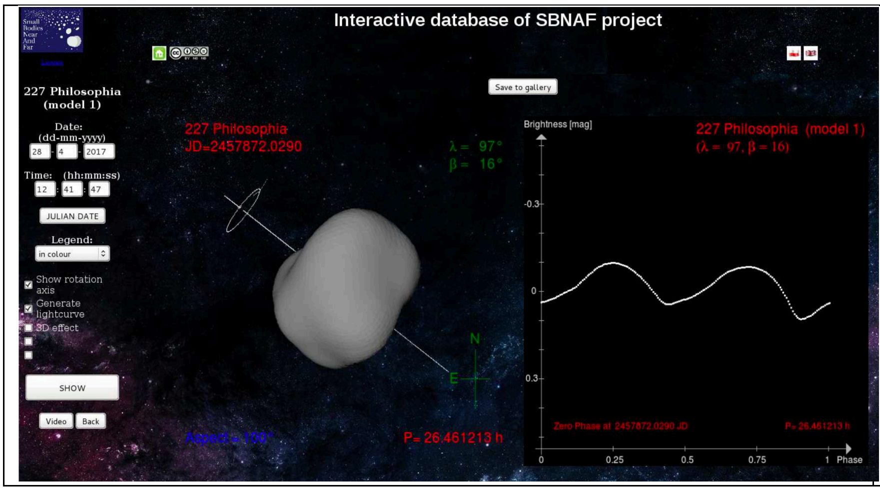
5. Technical results

There are different categories of technical results (see: http://www.mpe.mpg.de/~tmueller/sbnaf/results.html):

a) Tools & Services:

The Interactive Service for Asteroid Models (ISAM[6]) contains shape models for more than 900 asteroids. It allows to (i) to display an asteroid orientation as seen from Earth at any date; (ii) to generate lightcurves; (iii) to animate the rotation; (iv) to produce 3D views; and (v) to conduct shape and lighting analysis. D3.2 on "Prediction of shape orientations" is closely related and explains more details.

[6] http://isam.astro.amu.edu.pl/



Example view of the "orientation" mode of the ISAM service. One of our SAGE models is displayed together with the corresponding lightcurve for the given viewing geometry.

The Gaia-Groundbased Observational Service for Asteroids (Gaia-GOSA[7]) is an interactive tool which supports observers in planning photometric observations of asteroids. The asteroid prediction tool is based on the Gaia orbit and scanning law provided by the European Space Agency and the ephemerides of Solar System bodies provided by the Minor Planet Center. These inputs have been coupled by a software tool developed and run by the Gaia Data Processing and Analysis Consortium (DPAC). D3.1 on "GOSA service upload" is closely related and explains more details.

As part of the SBNAF project, we prepare a database for thermal IR observations of small bodies (NEAs, MBAs, Trojans, Centaurs, TNOs). The database will include measurements from ground (mid-IR, submm, mm) and space (IRAS, MSX, AKARI, ISO, Spitzer, WISE, Herschel, Planck). The database is planned to be available to the planetary community in early 2019, well before the TherMoPS III workshop in Budapest. D2.5 and D2.6 are closely related (due dates in Sep 2018 and Mar 2019).

b) Products for the planetary community:

These products include: occultation predictions (D5.1, D5.2, D5.3), User Provided Data Products for the Herschel Science Archive (D2.1, D2.2, D2.3, D2.4), and the asteroid-related calibration products (all deliverables in WP4, also D6.2). More details can be found at http://www.mpe.mpg.de/~tmueller/sbnaf/results/bProducts.html.

c) Results, recommendations, recipes from the synergy work:

The results in this category are more difficult to describe since they are typically part of scientific publications. However, we want to point out a few synergy results which are connected to public deliverables during the first 18 months of the SBNAF project:

- D5.6 Observational publications
- D6.1 Occultation vs. thermal tools
- D6.2 Shape & spin solutions for primary calibrators
- D6.3 In-situ object properties
- D6.4 Gaia asteroid list
- D6.5 "Ground-truth" shape models
- D6.6 Thermally resolved shape models.

[7] http://www.gaiagosa.eu/

The content of these deliverables is summarized above. Within the deliverables we also point to the corresponding (past, ongoing, planned) publications.

6. Outreach activities

The major outreach activities are listed on our public page at http://www.mpe.mpg.de/~tmueller/sbnaf/outreach.html, separated into three categories: (i) outreach events; (ii) press releases and public articles; (iii) public relation activities, including also links, animations, and outreach material. We give some examples.

a) Outreach events

Here, we list selected events, but many more outreach activities are ongoing throughout the year where SBNAF team members are in contact with the public (schools, interested laymen, people of very different age and background):

- Multiple public talks, institute seminars, outreach activities, interviews, etc. on the **"Haumea-Ring-Satellite system"**, following up on the Nature publication "Ortiz et al. 2017, Nature 550, 219-223: The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation" in all SBNAF partner institutes
- Worldwide Asteroid Day, public event in Munich/Germany on June 30, 2016, with a SBNAF-related presentation programme and N24 TV coverage (was broadcasted in Sep/Oct 2016)
- Public presentations during the Perseid meteor shower with strong emphasis on SBNAF activities: on Aug 11, 2016 at Calar Alto Observatory (CAHA), Spain (two groups of about 50 visitors each), and on Aug 12, 2016 at Sierra Nevada Observatory (OSN), Spain (with about 250 visitors)
- Marie Skłodowska-Curie action: European Researchers Night (NIGHT), public Europe-wide event on Sep 30, 2016 with SBNAF presentations in different places:
    - In Granada/Spain: La Noche Europea de los Investigadores
    - In Poznan/Poland: Small Bodies: Near and Far
- Stellar occultation by Haumea on Jan 21, 2017, coordination of observing activities all over Europe with about 40 observatories (professional & amateur) participating, making it one of the largest TNO occultation campaign ever; about 10 observatories have detected the event successfully
- Cita con las estrellas, El Corte Ingles, Malaga: "El cinturón trans-Neptuniano: Esos pequeños/grandes mundos más allá de Neptuno" (The transneptunian belt: those small/large worlds beyond Neptune), given on Mar 2, 2017
- Public lectures/seminars with sky shows at Poznań observatory
    - Public lecture on "Dwa światy: planetoidy Ceres i Vesta" (Ceres and Vesta asteroid studies), Dec 9, 2016
    - Presentation "Rekonstrukcja kształtów planetoid z obserwacji radarowych", as part of the seminar "Modern Trends in Physics Research", AMU Faculty of Physics, Jan 27, 2017
    - Presentation "Badanie rotacji i kształów planetoid", Astronomical Observatory of Warsaw University, Feb 28, 2017
    - Presentation "Fotometria, modelowanie i skalowanie planetoid o długich okresach i niskich amplitudach", Toruń Centre for Astronomy, Nicolaus Copernicus University, May 15, 2017
- Paisajes del Sistema Solar, Parque de las Ciencias de Granada, Feria del Libro de Granada, Apr 22, 2017
- Worldwide Asteroid Day, public event on June 30, 2017:

- Public "round table" event with several SBNAF asteroid experts at IAA/Granada on June 28, 2017
- Public talk on asteroid risk/defence at the Volkssternwarte München by NEOSHIELD-2 experts, supported by SBNAF members, on June 30, 2017
- Public talk at ESO on "The Fascinating World of Asteroids", following up on the Worldwide Asteroid Day, July 13, 2017
- Worldwide Asteroid Day related internship at MPE (4 young students, supervised by SBNAF members) in July 2017

- Marie Skłodowska-Curie action: European Researchers Night (NIGHT), public Europe-wide event on Sep 30, 2017:
  - SBNAF presentation in Granada/Spain
  - Preparation of multiple 3-D printed asteroid models, designed for outreach activities including blind people
- Public “Open House” day at the research campus Garching, Germany (Oct. 2017) with about 1,800 visitors at MPE:
  - public talk “Exotische Welten: Asteroiden, Kometen und Planeten”
  - kids program (with about 300 children), including activities like “Touch an asteroid“, display of several posters on small bodies, impact risk, overview of the solar system, planet X, etc., including also 3-D printed asteroids

b) Press releases and public articles

All press releases and articles are available on our SBNAF web pages.

2017:

- Haumea of the Outer Solar System (NASA's Astronomy Picture of the Day APOD from Oct 17, 2017)
- Astronomers discover ring around dwarf planet Haumea (HORIZON, The EU research & Innovation Magazine, 11 Oct 2017)
- Haumea, the most peculiar of Pluto companions, has a ring around it (Instituto de Astrofisíca de Andalucía, IAA-CSIC; 11 Oct 2017; English/Spanish)
- Ring around a dwarf planet detected (MPE/MPG press release; Oct 12, 2017; English/German)
- Haumea - the first dwarf planet with rings (Institute Astronomical Observatory, Faculty of Physics Adam Mickiewicz University in Poznań; Oct 12, 2017; English/Polish)
- World-wide press coverage of the Haumea Nature paper in many languages: The Guardian, New Scientist, Space.com, Science Magazin, Scientific American, Daily Mail, National Geographic, ABC, Planetary.org, The Verge, Science alert, Universe Today, Phys.org, Metro/UK, Arab News, Spaceref.com, Ghana Nation, GIZMODO, YouTube, Europa Press, Agenia SINC, El País, El Mundo, ABC/Spain, La Vanguardia, El Confidencial, Milenio, Canal Sur (min 11:22), iVoox, Nauka w Polsce, facebook.com, DAN TRI, Vietnam, Twitter (Carlos Moedas, European Commissioner for Research, Science & Innovation), Academic Film Studio of AMU, Poland, etc.
- Not the mother of meteorites (ESO Press Release; June 19, 2017)
- Hubble Spots Moon Around Third Largest Dwarf Planet (NASA, Hubble press release May 18, 2017)
- New asteroids named to honour astronomers from Poznań: group picture & press release & Poznańscy astronomowie mają swoje planetoidy! & Kolejne planetoidy oznaczone nazwiskami astronomów z UAM

- Meteoroides, Meteoros Y Meteoritos, Cómo se diferencian? (Revista de divulgación científica: Ciencia para todos los Públicos, Mar 2017)

2016:

- TNO 2016 BP81 discovery in Kepler-K2 data (MPS 749584 from Dec 11, 2016)
- NEA 2015 BO519 discovery in Kepler-K2 data (MPS 747529 from Dec 5, 2016)
- Kepler has caught hundreds of asteroids (Phys.org, Oct-24, 2016)
- Big Kuiper Object 2007 OR10 Has a Moon (Sky&Telescope Oct. 21, 2016)
- 2007 OR10 has a moon! (DPS/EPSC conference news, Oct. 19, 2016)
- Plutón, Plutón ..., Quién te ha visto y quién te ve (Información Actualidad Astronómica, revista.iaa.es, Oct. 2016)
- Radarkarte eines Asteroiden (Sterne & Weltraum, SuW 08/2016, Expert Answer)
- 2007 OR10: Largest Unnamed World in the Solar System (NASA JPL News May 11, 2016): combined Kepler & Herschel & ground-based data

c) Public relation activities

In this category, we provide a collection of images, YouTube movies, TV documentaries, tools, links to useful pages, etc., all related to SBNAF topics, most of them produced by the SBNAF team. The products of general interest are available from our public web page at http://www.mpe.mpg.de/~tmueller/sbnaf/outreach.html.
In addition, there are a number of outreach products to be used by team members for all kind of outreach activities (only available from our internal web page[8]).

7. Discussion and outlook

Our benchmark project includes several objects with ground-truth information from interplanetary missions. This kind of ground-truth information is unique in astronomy and leads to wide applications for objects without ground-truth information relevant to various projects in the planetary community outside SBNAF. It helps us to investigate limitations of current modelling techniques, to refine them beyond the state of the art, and to provide strategies for optimized observing campaigns at visual and thermal wavelengths.

Our tools and scientific results will contribute to the Basic Science demanded by the growing focus of Industry on mining asteroids and in-situ resource utilisation. The SBNAF results are immediately available to the astronomical community and to many amateur astronomers. Thanks to the occultation predictions and Gaia-GOSA services, amateur observers are providing substantial support for our project and spurring interest on our small-body studies among the general public. Along with other public outreach activities, this helps to broaden society's appreciation of our field, which is often reduced to the "impact hazard" question, and of astronomy and science in general. For example, our work is also scientifically relevant to profound problems such as the formation and evolution of our Solar System or the delivery of water and complex organic molecules to Earth.

From our point of view, the SBNAF project turned out to be very successful and productive. In the first 18 months, we completed 26 deliverables (out of the 38 for the

[8] http://www.mpe.mpg.de/~tmueller/SBNAF/PUBLIC_OUTREACH/public_outreach.html

entire 3-year period) and reached 4 milestones (out of 15). The project is running very closely to the foreseen schedule in the SBNAF Grant Agreement. The close collaboration of four teams with very different expertise is key to assess small-body science from very different angles and to produce new tools, products and very interesting results and discoveries (see also the range of related press releases).
In addition to our plans laid out in the proposal, we would like to mention a few new ideas, opportunities, and developments:

- We submitted a SBNAF-related observing proposal responding to the JWST DDT-ERS call for early release science. The proposal was not successful. However, the JWST option will be an important avenue for the mid-term future of small-body science and we will push for several SBNAF-related smaller projects in the upcoming JWST GO call. We also have participations in three JWST GTO proposals related to SBNAF targets that will be executed in cycle 1 (currently foreseen in late 2019 and early 2020).
- Following up on the discovery of a ring around the dwarf planet Haumea, we are trying to characterize the multiple-body/ring system with ALMA in the submillimetre/millimetre range, and also with JWST in the thermal Infrared and with VLT at visual wavelengths.
- We took advantage of the Kepler-K2 observing options by submitting small-body related proposals for the cycles 8 (in 2016) to 18 (2018): see also related multiple publications.
- We also have accepted observing programmes on HST, SOFIA, VLT, and many other intermediate to large telescopes around the world.
- We started to look into possible science topics for the SKA[9], although this is will happen well after the end of the SBNAF project.

Outlook:
We are currently trying to find funding opportunities to continue our very successful collaboration beyond the end of the SBNAF project in March 2019.

[9] https://skatelescope.org/