Small Bodies Near and Far (SBNAF): a benchmark study on physical and thermal properties of small bodies in the Solar System[☆]

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Abstract

The combination of visible and thermal data from the ground and astrophysics space missions is key to improving the scientific understanding of near-Earth, main-belt, trojans, centaurs, and trans-Neptunian objects. To get full information on a small sample of selected bodies we combine different methods and techniques: lightcurve inversion, stellar occultations, thermophysical modeling, radiometric methods, radar ranging and adaptive optics imaging. The SBNAF project will derive size, spin and shape, thermal inertia, surface roughness, and in some cases bulk densities and even internal structure and composition, for objects out to the most distant regions in the Solar System. The applications to objects with ground-truth information allows us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. We present results from our project's first phase: the analysis of combined Herschel-

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October 26, 2017

KeplerK2 data and Herschel-occultation data for TNOs; synergy studies on large MBAs from combined high-quality visual and thermal data; establishment of well-known asteroids as celestial calibrators for far-infrared, sub-millimetre, and millimetre projects; first results on near-Earth asteroids properties from combined lightcurve, radar and thermal measurements, as well as the Hayabusa-2 mission target characterisation. We also introduce public web-services and tools for studies of small bodies in general.

1. Introduction

We conduct an EU Horizon 2020[1]-funded benchmark study[2] (2016-2019) that addresses critical points in reconstructing physical and thermal properties of near-Earth (NEA), main-belt (MBA), and trans-Neptunian objects (TNO). The combination of the visual and thermal data from ground and astrophysics space missions like Hubble[3], Kepler-K2[4], WISE/NEOWISE[5], IRAS[6], Herschel[7], Spitzer[8], AKARI[9], and others, is key to improving the scientific understanding

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[1]Research and Innovation programme of the European Union, see http://www.horizont2020.de/

[2]Scientific exploitation of astrophysics, comets, and planetary data:
https://ec.europa.eu/research/participants/portal/desktop/en/-opportunities/h2020/topics/compet-05-2015.html

[3]The Hubble Space Telescope, see http://hubblesite.org/

[4]The Kepler Space Telescope, see https://keplerscience.arc.nasa.gov/

[5]Wide-field Infrared Survey Explorer, see https://neowise.ipac.caltech.edu/

[6]Infrared Astronomical Satellite, see http://irsa.ipac.caltech.edu/IRASdocs/iras.html

[7]The Herschel Space Observatory, see http://sci.esa.int/herschel/

[8]The Spitzer Space Telescope, see http://www.spitzer.caltech.edu/

[9]The Infrared Imaging Satellite "AKARI" (ASTRO-F), see http://global.jaxa.jp/-projects/sat/astro_f/
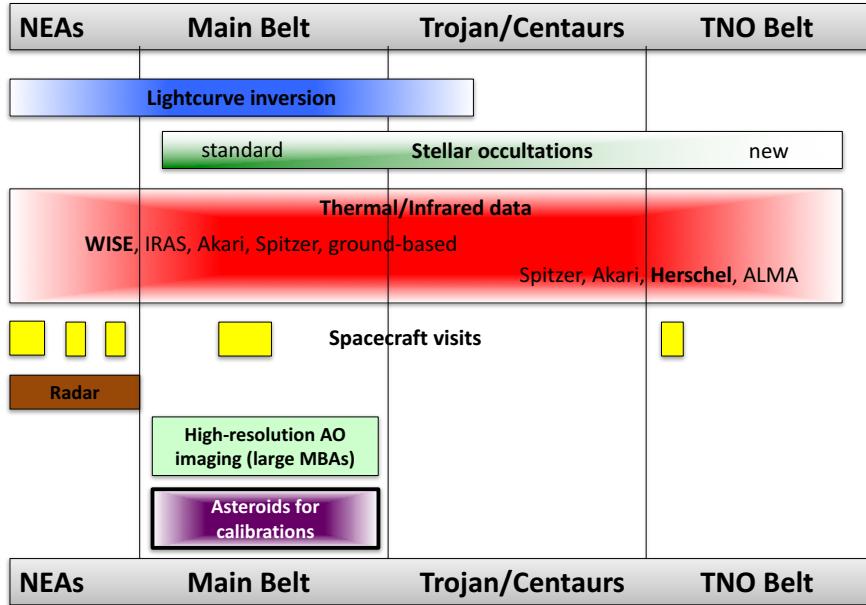
Figure 1: Overview of the different techniques applied to minor bodies at different distances from the Sun. The range where a given technique can be used is very restricted, making the reconstruction of object properties more complex and strongly dependent on the availability of suitable data.

of these objects. The development of new and improved tools is crucial for the interpretation of much larger data sets from WISE/NEOWISE, Gaia[10], JWST[11], or NEOShield-2[12]. Some of our results will be used in support of the operation of interplanetary missions, and for the exploitation of in-situ data. Depending on the availability of data, we combine different methods and techniques to get full information on selected bodies. Figure 1 shows the typical data and applicability of techniques as a function of distance from the Sun: lightcurve inversion,

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[10] Astrometric space observatory of the European Space Agency, see `http://sci.esa.int/-gaia/`

[11] James Webb Space Telescope, see `https://www.jwst.nasa.gov/`

[12] EU-funded project on "Science and Technology for Near-Earth Object Impact Prevention, see `http://www.neoshield.eu/science-technology-asteroid-impact/`

stellar occultations, thermal/infrared data (for thermophysical modeling and radiometric methods), radar ranging and adaptive optics imaging. The applications to objects with ground-truth information from interplanetary missions Hayabusa[13], NEAR-Shoemaker[14], Rosetta[15], DAWN[16], or New Horizons[17] (see yellow blocks in Fig. 1) allows us to advance the techniques beyond the current state-of-the-art and to assess the limitations of each method. Another important aim is to build accurate thermophysical asteroid models to establish new primary and secondary celestial calibrators for the far-infrared (far-IR), sub-millimeter (submm), and millimeter (mm) range (ALMA[18], SOFIA[19], APEX[20], IRAM[21], and others), as well as to provide a link to the high-quality calibration standards of Herschel and Planck[22]. The SBNAF project will derive physical, thermal, and compositional properties for small bodies throughout the Solar System. The target list comprises recent interplanetary mission targets, two samples of main-belt objects, representatives of the Trojan and Centaur populations, and all known dwarf planets (and candidates) beyond Neptune.

We introduce the relevant observing techniques (Sect. 2), our target sample (Sect. 3) and the related science questions. Selected results from our project's first year will be discussed in Section 4, new tools and web-services for studies of small bodies will be presented in Section 5. We conclude with an outlook (Sect. 6) for the next project phases.

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[13]Asteroid Explorer of the Japan Aerospace Exploration Agency (JAXA), see `http://global.jaxa.jp/projects/sat/muses_c/`

[14]The Near Earth Asteroid Rendezvous âĂŞ Shoemaker mission, see `https://solarsystem.nasa.gov/missions/near`

[15]Comet mission by ESA, see `http://sci.esa.int/rosetta/`

[16]Space probe to the asteroids Vesta and Ceres, see `https://dawn.jpl.nasa.gov/`

[17]NASA mission to Pluto, see `http://pluto.jhuapl.edu/`

[18]The Atacama Large Millimeter/submillimeter Array, see `http://www.almaobservatory.org/`

[19]Stratospheric Observatory for Infrared Astronomy, see `https://www.sofia.usra.edu/`

[20]Atacama Pathfinder EXperiment, see `http://www.apex-telescope.org/`

[21]Radio telescopes operated by the Institute for Radio Astronomy in the Millimeter Range (IRAM), see `http://www.iram-institute.org/`

[22]ESA's Planck space telescope, see `http://sci.esa.int/planck/`

2. Observing techniques

Small bodies are typically not resolved and models are needed to translate disc-integrated signals into physical properties. The SBNAF project will take advantage of existing observational data taken remotely from ground-based observatories and astrophysical missions, but we will also conduct (mainly photometric) measurements of a set of selected targets to vitally enhance the amount of information we can derive from them.

2.1. Lightcurves in the visible

Lightcurve inversion techniques are used to find an object's rotation period, its shape and spin-axis orientation. It requires the availability of multi-epoch and multi-apparition lightcurve measurements of sufficient quality. These kind of data are only available for NEAs, MBAs, and very few more distant bodies (see Fig. 1).
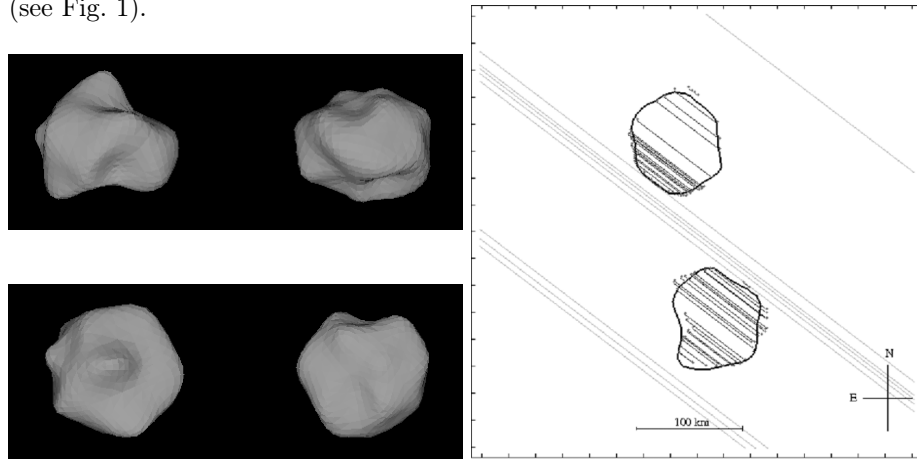

Figure 2: Left: Shape models for two components of the binary asteroid (90) Antiope obtained with the inversion of lightcurves using the SAGE algorithm for non-convex shapes (Bartczak et al. [2014]) in an equatorial view (top) and polar view (bottom). Right: A comparison between the stellar occultation chords and the projected non-convex shape solution.

Traditional, dense lightcurves are today available for over 10 000 asteroids.

The data sets are stored in the LCDB[23] database (Warner et al. [2009]) which is being regularly updated. Apart from continuous lightcurves, also an increasing number of so called "sparse data" recently appear, which are sparse in time absolute photometric measurements, usually obtained as a result or byproduct of wide-field surveys. In some cases the latter allow for finding rotational periods (Waszczak et al. [2015]), or spin axis position determinations (Ďurech et al. [2016]) for a large number of tagets.

Sparse lightcurve data are scientifically interesting (e.g., for searching for close and contact binaries via their diagnostic large lightcurve amplitude; Sonnett et al. [2015]), but the shape information content is very limited. For precise shape reconstruction there are much more stringent demands for the lightcurve data, which should be dense, low-noise, and come from a wide range of viewing geometries. Consequently, in order to reconstruct detailed shapes of asteroids, well coordinated campaigns are needed. The key is to complement already available data (stored in e.g. ALCDEF[24], or in APC[25] databases) with observations in different geometries, to probe the lightcurve changes over various aspect and phase angles. Because of the high demand of observing time, precise shape models can only be obtained for a small number of asteroids.

The field of spin and shape modelling of asteroids has seen a huge development in recent years. Since the introduction of the lightcurve inversion technique at the beginning of the last decade (Kaasalainen & Torppa [2001a]; Kaasalainen at al. [2001b]), over 900 spin and shape models have been published (e.g., Hanuš at al. [2013]; Marciniak et al. [2012]), usually based on sparse data. First attempts of multi-data inversion have been made in the last years (e.g., KOALA code, Carry et al. [2012]; ADAM algorithm, Viikinkoski et al. [2015]). Previously obtained shape models have also been size-scaled using data from stellar occultations (Ďurech et al. [2011]). In this way, it was shown that many inver-

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[23]Asteroid Light Curve Database at `http://alcdef.org/`
[24]The Asteroid Lightcurve Data Exchange Format, see `http://alcdef.org/`
[25]The Asteroid Photometric Catalog, see `http://asteroid.astro.helsinki.fi/apc`

sion solutions fit the data from independent methods. It has also been demonstrated recently, that lightcurves alone contain enough information for reliable non-convex modelling (the SAGE algorithm, Bartczak et al. [2014, 2017]; see Fig. 2).

Today, there is a possibility to join many types of complementary data to construct full physical models of asteroids, which would be an invaluable cornerstone for calibration of various methods and extrapolating gained knowledge to the whole range of objects, especially those with less rich available data sets. For example with thermal infrared (IR) data we see emission influenced by the thermal inertia and roughness of the surface and also sub-surface emission at submm/mm wavelengths, which makes a direct comparison with optical lightcurves more complex (see also discussion in Müller et al. [2017b]). Thermal data may also bear contributions from non-illuminated, yet warm parts of the surface (e.g., Nuggent et al. [2017]). Studying the relation of these two types of data on the basis of a few well-studied objects will help in developing a tool with great potential to infer information on albedo, size, spin, thermal inertia, and large-scale surface and regolith characteristics.

Physical properties of asteroid surfaces are the missing link in e.g. YORP effect modelling, which has been shown to change the spin frequencies and spin axis positions of small and medium-sized asteroids (Vokrouhlicky et al. [2003]). However, widely applicable small-body modelling techniques based on such varied sources of data (optical and thermal) is still missing. Thus we are going to address these issues in the present project. This way we will establish strong foundations for further studies of asteroid physical properties.

2.2. Radar technique

Radar is a technique used to retrieve information about asteroids. Its uniqueness lies in the observer's control of the transmitted signal, which is not the case in other techniques, like photometry. Thus, radar observations can be described as an experiment (Ostro et al. [2002], and references therein).

Only NEAs and MBAs that pass sufficiently close to Earth can be observed

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by radar, as the signal from the telescope fades very quickly with distance (see Fig. 1). Signals are sent from radio telescope and they bounce off the surface of the target body to be then recorded back on Earth. Asteroids come in variety of shapes, and the signal travels different distance depending on the part of asteroid that it hits. The echo (returning signal) arrives at different times, which can be translated into a size estimate. Since asteroids rotate, we can use this phenomena and take advantage of the Doppler effect. When the light emitting (or reflecting) objects (or surface elements) move towards the observer the registered light will have higher frequency ("blue-shifted") than the emitted (reflected) light. Similarly, if the object is moving away, its frequency is lower, and the light is "red-shifted". When an asteroid rotates, surface elements farther from the spin axis move at higher velocities. As a result, every pixel on radar-echo image is an intensity of returning signal at given time delay (distance) and frequency (velocity).

If we want to use radar images to model an asteroid, we have to simulate radar observations of a model object and compare it with observations. The model object is then modified in complicated patterns until the model echo matches the observed echo. This method works best when the object's spin properties are known and sufficient good-quality visible lightcurves are available.

2.3. Occultations

It is a simple measurement technique to derive the size and the projected cross section of a small body in a direct way. The basis is to predict when the particular body will pass in front of a certain star. One simply measures the flux of the star before, during and after the occultation from a few locations on Earth within the predicted shadow. It provides area-equivalent diameters with kilometric accuracy and it allows to determine the projected shape (a 2-D snapshot) of the body. It can reveal the presence of atmospheres with pressures down to a nano-bar (nbar) level, discover possible satellites, rings or material orbiting around a given object (see Fig. 3). Stellar occultations of planets, satellites (including the Moon) and also minor bodies (Elliot [1979]; Elliot & Young

[1992]) have been recorded over the last decades. This technique is well developed for these bodies, but it is only an emerging field for TNOs and Centaurs. Predicting and observing stellar occultations by TNOs is extremely difficult and challenging because the angular diameters of TNOs are very small and neither the stellar catalogues nor the TNOs orbits have the accuracy required to make reliable predictions well in advance.

A multi-chord stellar occultation by TNOs allows us to determine the projected shape and orientation of the body in the plane of the sky at the moment of the occultation. However, this information is insufficient to determine the true 3D shape of the body and its spin axis orientation in space. Combining the occultation-derived information with rotational lightcurves one can distinguish whether the 3D shape of the body is an oblate spheroid or a Jacobi ellipsoid. Usually, a very low TNO lightcurve amplitude implies a MacLaurin oblate shape, whereas amplitudes larger than 0.15 mag imply Jacobi shapes (Duffard et al. [2009]). But the spin axis orientation is still not well constrained (unless many high-precision rotational lightcurves spanning many years exist). Modelling thermal observations can be of great help in this regard. It allows us to put tighter constraints on the spin axis orientation by modelling the thermal output of the object. The basic parameters that can be constrained with thermophysical models are the size, shape, albedo, rotation rate (sometimes even the direction of rotation), the spin-axis orientation, and surface properties such as e.g. thermal inertia. Given that the occultation timings provides a very accurate size, shape and albedo, and if the rotation period is also known from the rotational lightcurves, the remaining parameters can be tightly constrained by combining these techniques. Thus, the combination of occultation results, optical lightcurves and thermal measurements allows us to reconstruct a full 3D shape and spin axis orientation in space. Once this all is known, bulk densities can be determined accurately using the Chandrasekhar figures of equilibrium formalism. This works very well for icy dwarf planets (mostly large TNOs) which are expected to be in hydrostatic equilibrium.

One example of the power of this technique is brought by the work of Ortiz

et al. ([2012]), who found a radius of the TNO named Makemake to be 1430 ± 9 km, and a hint of an atmosphere. Recently, the existence of rings around two Centaurs has been discovered by means of stellar occultation: around (10199) Chariklo by Braga-Ribas et al. ([2014]) and around (2060) Chiron by Ortiz et al. ([2015]).
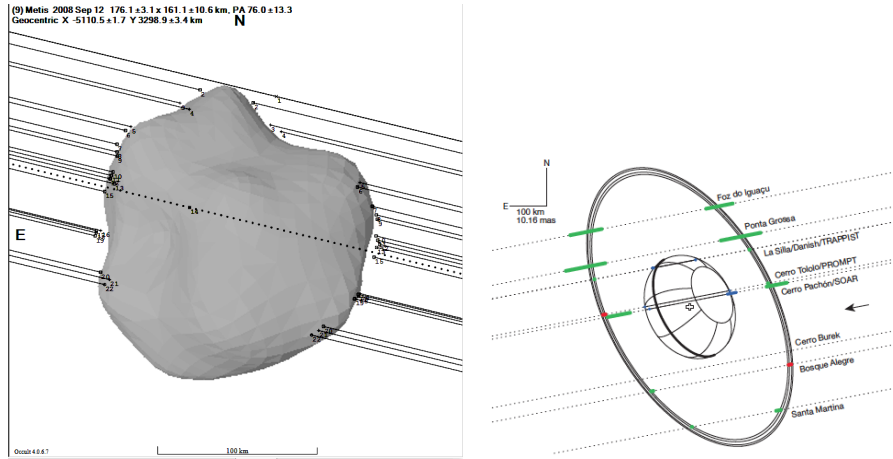

Figure 3: Left panel: dense telescopic observations (chords) of the stellar occultation by (9) Metis revealing the shape of the occulting body, with the superimposed independent shape model based exclusively on lightcurves inversion technique (Bartczak et al. [2014a]). Right panel: observations of the stellar occultation by (10199) Chariklo, where the presence of rings around a minor body was discovered for the first time (Braga-Ribas et al. [2014]).

2.4. Radiometric technique

This technique refers to the determination of the radius of the small body by fitting thermal emission models to observed thermal flux densities. The first applications of these techniques date back to the 1970's (for a recent review, see Delbo et al. [2015]). In a nutshell, the warmer a body is, the higher its emitted flux needs to be in order to stay in thermal equilibrium. Main belt asteroid surfaces are around 300 K and are best observed at around 10 μm (data from ground and space), TNOs surfaces are at around 30 - 40 K so the best wavelength range to observe them is between 70 to 100 μm (data are mainly coming from space projects). Two main radiometric methods allow the exploitation

of mid- and far-infrared thermal data with the goal to obtain size and albedo of asteroids: the Standard Thermal Model (STM; Lebofsky et al. [1986]), and the near-Earth asteroid thermal model (NEATM; Harris [1998]). On the other hand, if the shape and rotational properties of the object are known, we can model instantaneous surface temperatures accounting for the heat conductivity of the material as well as surface roughness. These are typically called "thermophysical models" (TPM; see references in Harris & Lagerros [2002] or Delbo et al. [2015]). If the shapes have no absolute scale, as it is the case for those derived from light curve inversion techniques for example, TPMs can help find the best scaling factors. The corresponding volume can be used to find more reliable equivalent diameters, or densities in cases where the asteroid mass is known. If multi-epoch thermal data are available for a given object, then it is possible to derive reliable thermal properties (thermal inertia, thermal conductivity), to estimate grain sizes on the surface or to do a simple study on the expected surface roughness (see Delbo et al. [2015] and references therein). The radiometric techniques work for all IR-detectable bodies in the Solar System (see Fig. 1). A recent example for radiometric applications for a large sample of Mars-crossing asteroids was presented by Alí-Lagoa et al. ([2017]). The "TNOs-are-cool" Herschel Space Observatory Key project (a large Herschel project with more tan 370 h of granted time) has gathered thermal data for more than 130 TNOs (Müller et al. [2009]; Kiss et al. [2013]; Lellouch et al. [2013]; Lacerda et al. [2014]). A good example of capabilities of the radiometric method based on Herschel observations is a study of the very distant (88 AU) TNO named Sedna. Pál et al. ([2012]) derived a diameter of 995 ± 80 km and geometric albedo of 0.32 ± 0.06. Sedna is not easily accessible otherwise.

2.5. Direct imaging techniques

Direct imaging techniques are related to measurements by large ground or space telescopes or by using data from interplanetary missions. The targets are spatially resolved in the obtained images. Size and shape information can then be extracted directly. Direct, accurate measurements of asteroid physi-
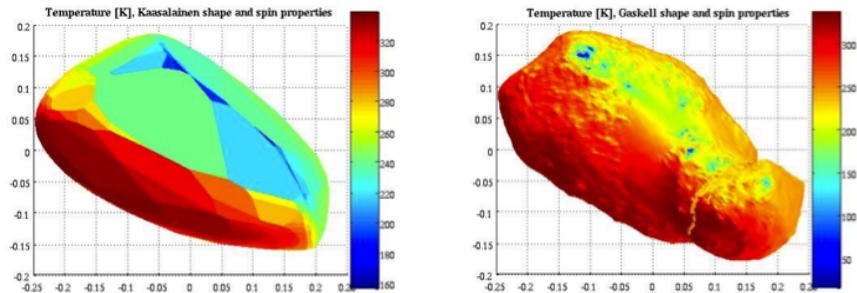
Figure 4: Comparison of the shape model for Itokawa with 204 facets (left) from lightcurve inversion technique, and a much more detailed shape model with 49152 facets (right) based on in-situ measurements from the Hayabusa mission. Figure and thermo-physical model adapted from Müller et al. [2014a].

cal properties are, meanwhile, possible for the largest several hundreds asteroids. They can be spatially resolved using the Hubble Space Telescope (HST) or large ground-based telescopes equipped with adaptive optics (AO) on the world's largest telescopes (Keck[26], VLT[27], and Gemini[28]). The AO systems today are capable of providing images close to the diffraction limit of the telescope at shorter wavelengths ($<1.6\,\mu$m), hence with an angular resolution of $\approx$33 milli-arcsecond (mas). Combining this technique with lightcurve inversion modelling it is possible to derive the volume-equivalent diameters for asteroids with typical uncertainties lower than 10%, caused by both the uncertainty in the size of the AO contour and the convex shape model imperfections. It can also remove the inherent mirror pole ambiguity of lightcurve inversion models (Marchis et al. [2006]; Hanuš et al. [2013a]). AO techniques are also capable of discovering binary systems which are important for studies on internal structure

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[26]W. M. Keck Observatory AO systems: see https://www2.keck.hawaii.edu/optics/ao/

[27]More information about the AO systems of the Very Large Telescope of the European Southern Observatory ESO can be found at http://www.eso.org/sci/facilities/develop/-ao/sys.html

[28]More information about the AO systems of the Gemini Observatory is given at http://www.gemini.edu/sciops/instruments/adaptive-optics

and composition through density determinations (via mass determination from Kepler's 3rd law; e.g., Merline et al. [2002]; Marchis et al. [2005]; Descamps et al. [2007]).

3. Targets and scientific questions

For our benchmark study on minor bodies we selected important targets which were already visited by spacecraft (or will be visited soon), which have a wealth of data from different observing techniques available (or are candidates for being observed with new techniques), but also those which are or will be useful in the calibration context, or which will allow us to address or answer specific scientific questions. The target list is not completely fixed and new objects –like the Halloween NEA 2015 TB$_{145}$ (Müller et al. [2017a])– can be included, if we see great observing and/or modelling prospects. Other targets might eventually be set aside for lack of data or data quality reasons.

3.1. Near-Earth asteroids

Several NEAs have already been visited by interplanetary missions. We selected the following objects:

- (433) Eros (visited by NEAR-Shoemaker mission)

- (25143) Itokawa (visited by Hayabusa mission)

- (162173) Ryugu (Hayabusa-2 mission; arrival in 2018)

- (101955) Bennu (OSIRIS-REx mission; arrival in 2018)

- 2015 TB$_{145}$ ("Halloween 2015 asteroid"; near-Earth flyby)

The selection was done on the basis of available visual and thermal data and the knowledge of object properties from in-situ studies. The objects have a wealth of visual lightcurve observations available, allowing the determination of shape and spin information via lightcurve inversion techniques. For Eros and Itokawa successful radar measurements have been conducted. All NEAs

have thermal measurements from different origin, covering wide wavelength and phase angle ranges.

The work on these targets will help us to verify the reconstruction of shapes (convex and non-convex solutions) from multi-apparition lightcurves, in direct comparison with true object shape and spin properties from in-situ measurements. Radiometric models "translate" infrared fluxes into size and albedo solutions, but how accurate are these radiometric sizes? Is it possible to constrain the spin-axis orientation from thermal measurements? Another key science goal is related to the influence of thermal inertia and surface roughness on the observed infrared fluxes (see for example Keihm et al. [2015]). Are there ways to break the degeneracy between these two properties which both influence the surface temperatures and the temperature distribution? Extensive work will be conducted on (162173) Ryugu, the Hayabusa-2 mission target: a pre-encounter characterisation of this small body will be used as a reference design model for the planning of the Hayabusa-2 close-distance operation, and in suppport of the interpretation of in-situ measurements. Our plans for Bennu, the OSIRIS-REx mission target, are restricted to independent tests of the current object properties specified in the Design Reference Asteroid document (Hergenrother et al. [2014]) by applying our new SBNAF tools.

3.2. Main-belt asteroids

For the main-belt asteroids we also selected a few reference objects with "ground-truth" information from interplanetary missions: Ceres & Vesta which were visited by DAWN, Lutetia and Gaspra which were seen during flybys of Rosetta and Galileo[29] missions, respectively. In addition, we selected a sample of large main-belt asteroids where the Gaia mission will eventually provide robust mass estimates (Gaia perturbers). Our goal is to collect existing data (lightcurves, thermal measurements, occultations, etc.) and conduct new

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[29]A NASA mission which studied Jupiter and its moons and several other small bodies, see
https://www.jpl.nasa.gov/missions/galileo/

measuremets that will allow us to derive reliable 3-D shape models and high-quality size estimates. The combination of Gaia and SBNAF properties will lead to object densities with unprecedented accuracy. Another MBA group - partly overlapping with the Gaia mass targets - is the "calibrator sample". Selected large and well-known main-belt asteroids are useful celestial calibrators for many ground-based and space projects, mainly at far-IR, submm, and mm wavelengths. For the calibration aspect it is usually necessary to observe bright, point-like sources where flux predictions are reliable. Direct applications are: absolute flux calibration for photometers, determination of relative spectral response functions, characterisation of instrument linearities, testing for filter leaks, or verification of satellite pointing and tracking capabilities. In addition, we added (911) Agamemnon as one of the very few better-known Trojan asteroids.

- (1) Ceres & (4) Vesta (visited by the DAWN mission)

- (21) Lutetia (Rosetta flyby)

- (951) Gaspra (Galileo flyby)

- Gaia mass sample (or Gaia perturbers)

- Calibrator sample (for thermal IR, submm, mm projects)

- (911) Agamemnon (unique Trojan asteroid)

The main science goals are similar to the ones for NEAs, but now for much larger objects, for low-conductivity surfaces covered by fine-grain regolith, more spherical shapes, and for targets of very different taxonomic types. Testing of radiometric solutions and shape-spin properties is as important as the support for Gaia and for calibration applications. The work on main-belt asteroids will also allow us to study subsurface emission at submm and mm wavelengths (data coming from ALMA, APEX, IRAM, but also Herschel and Planck).

3.3. Centaurs and trans-Neptunian objects

New tools have to be developed to characterise these very remote bodies. The distant objects can only be seen under small phase angles (and always very similar aspect angles) and standard lightcurve inversion techniques fail. Here, the lightcurves need to be combined with information from infrared data and occultation measurements to constrain physical and rotational properties. Thermal data became available recently (mainly from Spitzer and Herschel, partly also from ALMA and WISE), and still await a full scientific exploitation. Occultation measurements - however - are very difficult due to significant uncertainties in astrometric positions of the stars and - even more critical - of the distant solar system objects themselves. In this distant-object category we focus on large and 'observable' objects:

- Centaurs with thermal measurements (WISE, Spitzer, Herschel, others)

- large TNOs with thermal measurements (Spitzer, Herschel, ALMA)

- Centaurs/TNOs with stellar occultation information

- all dwarf planets and large dwarf planet candidates within the TNO population

The TNO/Centaur target sample is mainly driven by successful occultation observations, but recently we also obtained very high quality and long-coverage lightcurve measurements via the Kepler-K2 mission. These observations put strong constraints on object properties, and in combination with the thermal data will lead to significant improvements in the characterisation of Centaurs and TNOs. It will also be very interesting to phase in new ALMA observations at mm wavelengths: here we start to see subsurface emission telling us details about the top-layer surface properties, and related emissivity effects such as were seen with Herschel/PACS/SPIRE for a small sample of TNOs/Centaurs (Fornasier et al. [2013]).

4. Science results: synergies from ground and space

Remote observations and in-situ measurements of asteroids are considered highly complementary in nature: remote sensing shows the global picture, but transforming measured fluxes in physical quantities frequently depends upon model assumptions to describe surface properties. In-situ techniques measure physical quantities, such as size, shape, rotational properties, geometric albedo or surface details, in a more direct way. However, in-situ techniques are often limited in spatial/rotational/aspect coverage (flybys) and wavelength coverage (mainly visual and near-IR wavelengths). Mission targets are therefore important for comparing properties derived from disk-integrated measurements with those produced as output of the in-situ measurements. The associated benefits are: (i) the model techniques and output accuracies for remote, disk-integrated observations can be validated (e.g., Müller et al. [2014a] for the Hayabusa mission target (25143) Itokawa; O'Rourke et al. [2012] for the Rosetta flyby target (21) Lutetia); (ii) the improved and validated model techniques can then be applied to many similar objects easily accessible by remote observations, but which are not included in interplanetary mission studies. The pre-mission observations are also important for determining the object's thermal and physical conditions in support for the construction of the spacecraft and its instruments, and to prepare flyby, orbiting and landing scenarios.

We summarise a few key points arising from the combination of ground and space measurements:

- disk-resolved vs. disk-integrated measurements

- different viewing geometries from ground and space

- long-term observation possibilities from ground vs. short single flyby events

- extended (infrared) wavelength coverage from space

- higher sensitivity from space (or close-up observations)

- long-term stable observations from space without weather, day/night or airmass issues

- testing of thermal model parameters (like surface roughness) vs. in-situ properties

- testing of mathematical shape/spin model solutions vs. in-situ properties

- assessment of errors, biases, limitations, etc. related to lightcurve inversion, radar, occultation, AO, or radiometric techniques

In the following projects we took advantage of the synergetic effect of combining observations from very different sources.

4.1. Thermal measurements from Herschel & Spitzer combined with occultation information

The multi-chord stellar occultation by the trans-Neptunian object (229762) 2007 UK$_{126}$ led to an area-equivalent radius (of an ellipse fit) of 319^{+14}_{-7} km, a geometric V-band albedo of $0.159^{+0.07}_{-0.013}$ and a possible body oblateness close to 0.1 (Benedetti-Rossi et al. [2016]). The combination of occultation results with thermal data from the Herschel Space Observatory allowed us to put additional constraints on the size, shape, possible spin-axis orientation, and thermal inertia (Γ = 2 - 3 Jm^{-2}s$^{-0.5}$K$^-$) of the main body, but also some upper limits on the satellite of 2007 UK$_{126}$ (Schindler et al. [2017]).

A similar approach was possible for the Plutino 2003 AZ$_{84}$ (Santos-Sanz et al. [2017]). The Herschel and Spitzer measurements, in combination with a successful occultation event, gave a consistent solution for the object's size and shape (close to a sphere) and favours a close to pole-on orientation of the spin axis. A new study combined four different occultation events for 2003 AZ$_{84}$ (Dias-Oliveira et al. [2017]) and came to the same conclusion that we are currently seeing the object close to pole-on. This is also consistent with the small amplitude of the optical lightcurve (around 0.07 mag).

A publication on the Eris-Dysnomia system as seen with the synergy of occultation and thermal emission measurements is currently in preparation (Kiss et

al., in preparation). The results of the first successful occultation measurements of Haumea (from January 21, 2017) will also be combined with the available thermal measurements from Herschel and Spitzer (Ortiz et al., in prep.).
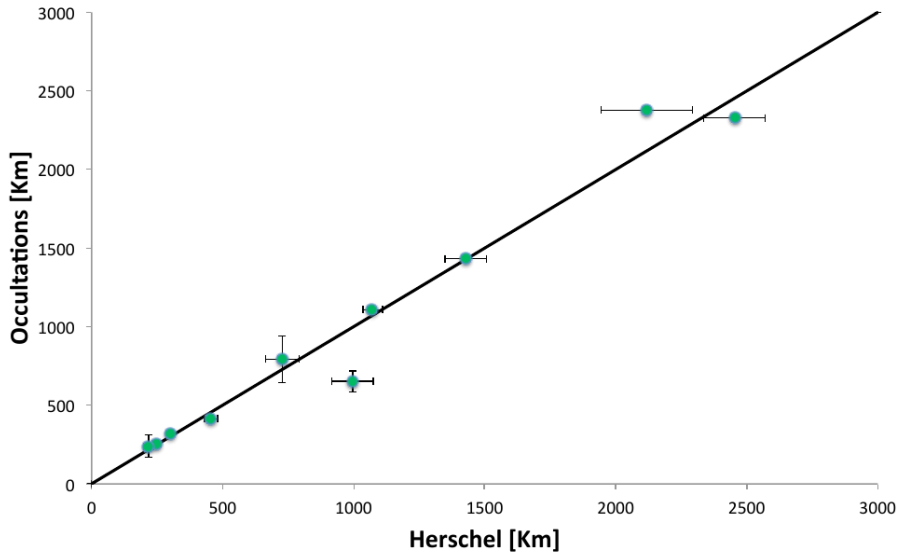

Figure 5: A comparison between TNO sizes derived from successful occultation events and radiometric sizes (mainly related to the "TNOs-are-Cool" Herschel key project; Müller et al. [2009]). Ourliers are explained in the text.

Figure 5 shows a comparison between size determinations based on radiometric techniques (mainly based on Herschel thermal measurements) and occultation measurements. There is a very good agreement between both completely independent solutions. The point out of the line near 1000 km is Sedna that has so-far only a single chord occultation. In case of Pluto (second outlier with the largest occultation size in Fig. 5) the (standard) radiometric method is uncertain. The atmosphere, strong albedo variations and the large satellite Charon would have to be considered to obtain a reliable radiometric size.

Ideas on how to push the field of TNO occultations are presented in Santos-Sanz et al. ([2016]). In the near-term future JWST will provide opportunities to observe stellar occultations by TNOs (and other objects) with unprecedented accuracy. At the same time, JWST also has the option to measure the thermal

emission up to $28\,\mu$m for many small bodies, including the largest TNOs and Centaurs.

4.2. Kepler-K2 lightcurves combined with thermal data

The irregular Neptune satellite Nereid was seen in a multiple-day observing campaign of the Kepler-K2 mission. The results were presented in a publication "Nereid from space: rotation, size and shape analysis from K2, Herschel and Spitzer observations" by Kiss et al. ([2016]).

The Kepler-K2 fields covered also more than 50 Trojan asteroids (Szabó G. et al. [2017]) and a large number of MBAs (Szabó R. et al. [2016]). Both samples comprise a fantastic laboratory for combined lightcurve-thermal studies. The Kepler-K2 lightcurves - sometimes complemented by auxiliary lightcurve measurements from ground - constrain the shape and spin properties of these objects. The thermal measurements (coming from IRAS, MSX, AKARI, WISE, and others) allow the scaling of the shape solutions, and lead to albedo and thermal characteristics for each object (this work is planned as part of the SBNAF project).

Another successful example of Kepler-K2 and Herschel synergies was presented by Pál et al. ([2016]): "Large Size and Slow Rotation of the Trans-Neptunian Object (225088) 2007 OR$_{10}$ Discovered from Herschel and K2 Observations". 2007 OR$_{10}$ is now considered as the "Largest Unnamed World in the Solar System" (NASA JPL News May 11, 2016). A deeper look at HST archive images of the same target revealed a small satellite (Marton et al. [2016]; Kiss et al. [2017]). Follow-up studies with HST are in preparation.

4.3. Visible and thermal photometric studies

Does the centaur (54598) Bienor have a ring system? Lightcurve studies over more than 15 years show a strong decline in amplitude and, combined with the spectroscopic detection of water ice, this would be best explained by rings (Fernández-Valenzuela et al. [2017]). The main body seems to have an extreme shape approximated by a triaxial Jacobi ellipsoid, and a possible density between

0.6 and $0.7\,\mathrm{gcm^{-3}}$. Thermal measurements from Herschel (Duffard et al. [2014]) put constraints on size and albedo. Different spin-pole orientations are dicussed in the light of visible and thermal measurements, but follow-up observations or a high-quality stellar occultation are needed to clarify the true nature of this exotic centaur.

Double-peaked visible lightcurves indicate that 2008 OG_{19} is a highly elongated TNO (Fernández-Valenzuela et al. [2016]). The object has a rotation period of about $8.7\,\mathrm{h}$ and a large peak-to-valley lightcurve amplitude of $0.44\,\mathrm{mag}$. A size estimate of $619^{+56}_{-113}\,\mathrm{km}$ is related to an average albedo for scattered disk objects (Santos-Sanz et al. [2012]). Assuming the object to be in hydrostatic equilibrium gives a lower limit for its bulk density of just above 0.5 $\mathrm{gcm^{-3}}$. It belongs to the dwarf planet candidates and seems to resemble the strangely shaped classical Kuiper Belt object Varuna. As for other large TNOs, the interpretation of visible lightcurves benefits from having thermal measurements which are less affected by albedo variations on the surface (see other TNO cases mentioned before). In the near-term future, it is expected that JWST will conduct thermal emission studies of selected and scientifically interesting TNOs like 2008 OG_{19}.

For very remote objects standard lightcurve inversion techniques fail to produce shape and spin solutions due to the small changes in aspect angles (as seen from a ground-based or near-Earth observing point). However, the rotational variability can tell us many things about these large and often icy bodies. Santos-Sanz et al. ([2017]) obtained thermal lightcurves of the dwarf planet Haumea, and the Plutinos 2003 VS_2 and 2003 AZ_{84} with Herschel Space Observatory-PACS. In addition to size, albedo and shape constraints, the authors also found very low thermal inertias which seem to be explained best by a moderately porous regolith where the sub-cm-sized amorphous ice grains have only loose contacts. Since crystalline water ice signatures are seen for Haumea, the best explanation points to the presence of amorphous ice at cm depths below a thin layer of transparent crystalline ice.

Recently, Müller et al. ([2017b]) and Perna et al. ([2017]) presented a study

on the NEA 162173 Ryugu, the target for the Hayabusa-2 mission. The almost spherical shape of the target together with the insufficient lightcurve quality required the application of radiometric and lightcurve inversion techniques in different ways to find the object's spin-axis orientation, its shape and to improve the quality of the key physical and thermal parameters. The work also showed the difficulties and problems occuring in combined visible and thermal photometric studies. The constraints on object properties strongly depend on the quality of the visible lightcurves, the observing/illumination geometries and wavelengths of the thermal measurements, and also on the validity of model concepts.

The Spitzer/Herschel sample contains about 30 multiple TNO systems. The satellite orbits of many of these binary and triple TNOs are sufficient to derive a system mass. The combination of the masses with volume estimates (coming either from radiometric or occultation sizes) determines the bulk density (e.g., Santos-Sanz et al. [2012]; Mommert et al. [2012]; Vilenius et al. [2012]). Kovalenko et al. ([2017]) presented densities ranging from below 0.5 to almost $4.0\,\mathrm{g\,cm^{-3}}$, with a moderately strong correlation between diameter and bulk density. Multiple TNOs also strongly correlate with heliocentric orbital inclination and with magnitude difference between components of multiple system. Single and multiple TNOs also show different size distributions, but here the small Centaurs (mainly single TNOs) and the large dwarf planets (almost all are multiple systems) cause a bias in the distributions. This work is also a nice example for the interplay between different techniques: high-resolution/AO imaging (HST and large ground-based telescopes) is needed to discover and characterise satellites, while thermal measurements and occultations are key to constraining the size and volume of these bodies.

The New Horizons mission provided a very detailed view of the Pluto-Charon system. But only through thermal measurements with Herschel's long-wavelength channels it was possible to see a strongly decreasing brightness temperature towards submm wavelengths (Lellouch et al. [2016]). The best explanation is a spectral emissivity that decreases steadily from 1 at 20-25 μm to

≈ 0.7 at $500\,\mu m$, similar to what is found for other icy bodies in the solar system (Fornasier et al. [2013]). The effect is likely related to a transparent top-layer surface combined with a strong dielectric constant.

4.4. Support for interplanetary missions

The JAXA Hayabusa-2 mission was approved in 2010 and launched on December 3, 2014. The spacecraft will arrive at the NEA 162173 Ryugu (1999 JU$_3$) in 2018 where it will perform a survey, land and obtain surface material, then depart in December 2019 and return to Earth in December 2020. We support the mission by providing key physical, rotational, thermal, and compositional properties of the mission target. Based on all available visible lightcurve observations and thermal emission measurements, we applied lightcurve inversion and radiometric techniques. The summary of our work (as of late 2016) is documented and discussed in Müller et al. ([2017b]). Our results are part of the Ryugu reference model which is widely used in the planning of mission operation scenarios, the satellite approach phase, touch-down simulations, landing site selection procedures, and also for outreach activities. The pre-encounter characterisation will also help to adjust temperature- and brightness-critical instrument settings. Ryugu will be one of the very few targets were preencounter properties - derived from disk-integrated remote observations - can be directly compared to in-situ properties. This will allow us to verify our model procedures and to consolidate the related error estimates.

A study on the NASA OSIRIS-REx mission target (101 955) Bennu (Müller et al. [2012]) contributed to the official "Design Reference Asteroid for the OSIRIS-REx Mission Target (101955) Bennu" (Hergenrother et al. [2014]). We plan to apply our SBNAF tools (lightcurve inversion, combination with radar and thermal measurements) to the available observational data to derive physical and thermal properties (and their uncertainties) for a direct comparison with in-situ findings (arrival of OSIRIS-REx at Bennu will be around September 2018).

A new field for the application of our tools and expertise is related to the

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topic of in-space utilisation of asteroids. In preparation of interplanetary missions with the goals of asteroid mining and resource utilisation for long-term missions and manned space exploration, it is necessary (i) to find suitable objects; (ii) to characterize the global objects properties (size, shape, rotation) and rough composition; (iii) to investigate surface and sub-surface characteristics (Graps et al. [2016]; Müller et al. [2017a]). The SBNAF project will contribute in different ways to the characterization of these small NEAs, in close contact to asteroid mining companies.

5. Tools and services for small bodies

5.1. SBNAF public website

The purpose of the SBNAF public website[30] is to share our scientific interest on small bodies with the astronomical community and the interested public. We document the progress and knowledge of the SBNAF project. We advertise outreach activities that we and other institutions around Europe organise. Ultimately, we hope to stir curiosity and to provoke questions about these rocky and icy bodies, some of which were around already during the formation of the planets in our solar system.

On our public website we present the basic facts about the SBNAF project, target lists, observing techniques, and all results (web services, tools, products, databases, predictions, etc.) for the general planetary science community. We also list all SBNAF-related publications, conference contributions, and outreach activities.

5.2. ISAM

The Interactive service for asteroid model visualisation (ISAM) is a web-based service where all kinds of asteroid shape models are provided, together with various tools to visualise shape solutions, illumination geometries, rotational properties, disk-integrated lightcurves, etc. The SBNAF-related spin and

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[30]http://www.mpe.mpg.de/~tmueller/sbnaf/

shape models will be provided to the community via the ISAM service[31], typically in the context of SBNAF project deliverables or after specific publications. Many of these shape and spin solutions are also used for other work packages (like for the Gaia or calibration samples). In the last stage of the project, the full models solutions (convex and non-convex shape solutions) with absolute sizes and model uncertainties will be published and provided to the scientific community by the ISAM service. This service is also of great help for a direct comparison between on-sky projected shape model solutions with results from an occultation event or from single-epoch AO images. The ISAM lightcurve prediction for a given shape and spin solution can be directly compared with lightcurve measurements or archive data (e.g., from the CDS[32] or from LCDB).

5.3. Gaia-GOSA

Gaia-Groundbased Observational Service for Asteroids (Gaia-GOSA[33]; Santana-Ros et al. [2014]; [2016]) is an interactive tool aiming to facilitate asteroid observers in contributing to the Gaia mission (European Space Agency) by gathering lightcurves of selected targets. GOSA users can plan their observing runs by selecting the visible targets for a given date, collaborate with other observers and upload the frames obtained. We are responsible for analyzing the data, publishing the results in the website and creating a lightcurve catalog. Once calibrated, lightcurves will be easily included in the analysis of Gaia data, which will allow to enhance the determination of asteroids' physical properties. This service is meanwhile used by a large community of observers to plan, conduct and provide dedicated asteroids measurements.

5.4. Calibration project

Celestial standards play a major role in observational astrophysics. They are needed to characterize the performance of instruments and are paramount for

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

[32]Centre de Données astronomiques de Strasbourg, see http://cdsweb.u-strasbg.fr/

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

photometric calibration. Large main-belt asteroids fill the flux gap between the submm calibrators Mars, Uranus and Neptune, and the mid-IR bright calibration stars. Space instruments at thermal infrared (IR) wavelengths use asteroids for various calibration purposes: pointing tests, absolute flux calibration, determination of the relative spectral response function, observing mode validation, cross-calibration aspects, and several other aspects where bright, point-like, easily accessible, and reliable sources are needed (Müller & Lagerros [2002]; Müller et al. [2014b]).

The SBNAF project supports worldwide calibration activities for ground-/airborne-/balloonborne-/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 Work Package 4[34] of the SBNAF project. The documents explain the calibration need, the reasons for using asteroids in the calibration context, and the various steps from simple model predictions for calibration planning purposes, up to the establishment of new primary calibrators for highly demanding applications. The asteroid-calibration activities are related to all infrared space projects (IRAS, MSX, Spitzer, AKARI, WISE, Herschel, Planck), but also to ongoing submm and mm observatories like ALMA, APEX, IRAM, or LMT, as well as for balloon-borne (BLAST) and airborne (SOFIA) projects. A recent large delivery of calibration products (1433 FITS files) includes specific model predictions for all Herschel observations of 28 asteroids (all large MBAs) which were used for various calibration activities for the three instruments PACS, SPIRE, and HIFI (see Herschel Ancillary Data Products[35]).

The calibration goals of projects like ALMA or Herschel are very ambitious and the traditional celestial calibration sources are often not sufficient, showing far-IR excess emission, variability, unsuitable flux levels or spectral slopes, or modelling shortcomings. Also the number of celestial calibrator sources is

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[34]http://www.mpe.mpg.de/~tmueller/sbnaf/results/WP4_AstCal.html

[35]https://www.cosmos.esa.int/web/herschel/ancillary-data-products

very small and often there are no sources available in a given observing campaign. The asteroids are therefore useful to complement existing calibration schemes. Currently, the highest demand is coming from Herschel and AKARI (post-operation calibration activities), SOFIA, ALMA, and sporadically also from other groundbased observatories like IRAM or APEX. In close contact with instrument calibration scientist we provide specific asteroid model predictions together with a documentation on the model input parameters and model quality issues. Our SBNAF goal for Herschel and AKARI is to make a quality upgrade for the already implemented asteroid calibration models.

5.5. Herschel Science Archive (HSA) user-provided products

The SBNAF project produces high-quality data products for small body observations of the Herschel Space Observatory. These products are based on sophisticated, solar-system specific reduction and calibration procedures. The products cover many Herschel science projects, as well as calibration observations.

Most Centaur and trans-Neptunian object observations were performed in the framework of the "TNOs are Cool!" Herschel Open Time Key Program (Müller et al., [2009]; [2010]), supplemented by some DDT observations of extreme objects (see e.g. Kiss et al., [2013]; Pál et al., [2015]). In these cases the standard HSA[36] product generation reduce the data in the co-moving frame and does not combine multiple observations of the same target. TNO observations were designed in a way that maps taken at different epochs can serve as mutual backgrounds and a proper combination of maps can eliminate the background, leaving the target to be the only notable source in the combined maps (for details, see Kiss et al., [2014]) - background elimination in the far-infrared is crucial due to the strong confusion noise (see e.g. Kiss et al., [2005]). The simplest maps of this kind are the *differential* maps, with one positive and one negative beam of the object. Further processing (*double-differential* maps) combines

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[36]http://archives.esac.esa.int/hsa/whsa/

these beams and provides a single beam of the target that is preferably used for photometry. These double-differential maps gave the best photometric accuracy among all Herschel/PACS scan maps observations (see e.g. the case of comet Hale-Bopp, Szabó et al., [2012]). Differential and double-differential maps combine up to eight observations, depending on the band used. *Supersky-subtracted* maps (Santos-Sanz et al., [2012], Kiss et al., [2014]) are also produced – in this case a 'target-free', combined background map is created and subtracted from the individual maps.

Similar techniques could be used in the case of near-Earth asteroids if the displacement of the target was sufficiently small within a specific scan map observation block (so-called repetition, see e.g. the case of Ryugu, Müller et al., [2017b]). In most near-Earth asteroid observation, however, the scan map data had to be reduced in the co-moving frame due to the fast apparent motion. In these cases our UPDPs[37] use a combination of observations different from that of the standard HSA products and are also reduced with an optimised pipeline, in many cases eliminating sub-blocks affected by instrumental effects. This optimised pipeline - both for near-Earth asteroids and TNO observations - include specifically selected high-pass filter, masking and de-glitching parameters, signal drift correction, and optimally chosen pixel size and back-projection pixel fraction values (for details, see Kiss et al., [2014]). Our UPDPs are provided as standard FITS files, accompanied by specific release notes (see HSC pages on UPDP[38]).

5.6. Occultation predictions

Based on publicly available and own tools, together with multiple campaigns of dedicated astrometric observations, we make regular predictions of occultation events produced by our SBNAF sample targets. Step-by-step we also phase in information from the Gaia mission to improve the accuracy of the predicted

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[37]User Provided Data Products

[38]https://www.cosmos.esa.int/web/herschel/user-provided-data-products

shadow paths. We focus on occultation predictions for Europe (mainly Spain) and South America (mainly Argentina, Chile, and neighbours) where we have own telescope facilities and close contacts with networks of well-trained observers. In the near-term future we might also include potentially interesting asteroid occultations of strong, compact radio sources, following up on the work by Lehtinen et al. ([2016]). The predictions of MBA events is, meanwhile, very reliable and easily possible via public tools (e.g., *Occult Watcher*[39] or the occultation prediction software *Occult*[40]). Our focus in the SBNAF project lies on the much more challenging predictions for TNOs and Centaurs. These distant objects have a very small projected size in the sky: ≈ 8 mas for a typical 100 km Centaur at 17 AU, ≈ 82 mas for the largest TNO (Pluto), and ≈ 14 mas for a 400 km TNO at 39 AU. This means that to catch a stellar occultation produced by one of these tiny bodies we must have a very accurate knowledge of their orbits and ephemeris, and we also need very precise star catalogues with accurate positions in the occultation track region. So far, the most accurate catalogs were the UCAC4 catalog with uncertainties of ≈ 15-100 mas (Zacharias et al. [2013]) and the (incomplete) URAT1 catalog with up to ≈ 2-3 times better astrometric precision (Zacharias et al. [2015]). The Gaia DR1 catalogue (Lindegren et al. [2016]) improves the situation for the star positions considerably. The uncertainties will be even smaller with future Gaia data releases (the second one is expected for April 2018[41]). However, the orbits of the TNOs and Centaurs are only poorly known and dominate often the prediction uncertainties. These objects need centuries or even more time to complete one orbit and up to now we have only observed a very small arc of their orbits. Here, it is often necessary to switch to relative astrometry with the target and star imaged together in the same field of view (FOV) in the months and weeks before a predicted event. The FOV must be large in order to have a significant number of astrometric

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[39]http://www.occultwatcher.net/

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

[41]https://www.cosmos.esa.int/web/gaia/release

references. In this way, one can achieve a high astrometric precision for TNOs up to $\approx$20 mas (Ortiz et al. [2011]), enough to predict the shadow path on Earth within $\approx$500 km. This technique has been succesful for $\approx$10 TNOs (see Fig. 5) and a few Centaurs. Large groups of observers are using these predictions to plan own observations for supporting these unique and scientifically important occultation events.

5.7. Database of calibrated thermal infrared measurements

One of the SBNAF goals is to produce a database for thermal infrared observations of small bodies. The SBNAF concept foresees to start with a database containing all available (published) thermal IR measurements for our selected samples of solar system targets, first for internal usage, later with open access to the public. The database should also have the future option (after the SBNAF project end) to include large amounts of thermal data for all solar system small bodies which have been detected at thermal IR wavelengths.

Our sample includes selected near-Earth, main-belt, trojans, Centaurs, and trans-Neptunian objects. All targets have significant amounts of thermal measurements from different satellite missions (IRAS, MSX, ISO, AKARI, Spitzer, Herschel, Wise, NEOWise), from SOFIA, and from ground. We assume that all objects appear as point sources (or point-like sources) and that the photometric measurements are corrected for aperture losses and well calibrated. For each dataset we will also give a short recipe on how to use the calibrated in-band fluxes in the context of radiometric techniques. The recipes include information about the instrument and calibration aspects, as well as the filter pass bands, saturation, non-linearity issues, and colour-correction procedures. The collection of infrared measurements in a unified way has the goal to better describe these targets by using all available data simultaneously. In this way, we also want to address a range of scientific questions (see Section 3).

For storing IR measurements in a database, we first focus on the essential basic entries: object identifier, observatory, measurement identifier, instrument/-band/filter/mode, start time of the observations, duration, measured in-band

flux (calibrated, aperture-/beam-corrected, non-linearity/saturation-corrected, etc.) and the corresponding flux error. A list of quality comments or other flags should also be possible. Some of the database entries could also have a link to auxiliary information, like project-/instrument pages, specific archives, relevant publications and documents.

In addition to the measured flux and error, it is needed to calculate also the mono-chromatic flux density at pre-defined reference wavelengths, to translate times from calendar to JD (with/without correction for light-travel time), to convert wavelengths to frequencies, to add absolute flux errors (if not done already), etc. For each measurement, it would also be useful to store (or calculate) information like the heliocentric, observer-centric distances, and the phase angle, or also orbital parameters. Optional parameters are RA, Dec, ObsEcLon, ObsEcLat, solar elongation, ecliptic helio-centric XYZ of the observer and the target, light-travel time, apparent motion of the object (all at observation mid-time). This could for example be done via the Callhorizons Python module[42]. It is planned to make these tools available together with the first database prototype. This database will gain importance in the context of planning and analysing JWST mid-IR measurements of small bodies.

5.8. Phase curve calculator & H-magnitude

When absolute photometry (placed on a standard photometric system) is available asteroid scattering properties related to the so-called opposition effect (caused by the backscattering mechanism) can be determined. This sort of observations typically involve photometric sky conditions and/or the presence of photometric standards in the field-of-view of the telescope. For accurate phase curves full lightcurves obtained every few degrees in phase angle are needed to determine the magnitude shifts between the measurements for a range of phase angles. Data obtained at various oppositions require aspect corrections and sparse data require even more calibrations to correct for lightcurve ampli-

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[42]https://pypi.python.org/pypi/CALLHORISONS

tude. Once the data have been properly calibrated we will fit the data using different fitting schemes depending on the quality of the data. The currently recommended IAU functions are the H, G1, G2 and H, G12 phase functions (Muinonen et al. [2010]). A variations of the H, G12, can be utilized for low quality data or when the taxonomic type of the fitted object is known. For low quality (magnitude uncertanities larger then $\sim 0.3\,\mathrm{mag}$), but numerous data it is recommended to perform the fitting in magnitude space (Penttila et al. [2016]) to avoid systematic biases. For high quality data the fitting can be done either in flux or magnitude space. In magnitude space the problem reduces to a linear one thus reducing the computational time. The uncertanities in phase curve parametes can be non-Gaussian, thus procedures like for example the bootstraping method are recommended to estimate the uncertainty. The scattering properties relate to regolith properties such as spectral type, albedo, porosity, and others (Oszkiewicz et al. [2011]; [2012], Shevchenko et al. [2016]) .Those relations are currently poorly determined and understood. Obtaining high number of accurate phase curves is therefore crucial in establishing those relationships and their implications to asteroid population as a whole. As part of SBNAF, we will document the procedures for the general users, and re-calculate phase curves and H-magnitudes (also very relevant for albedo calculations) for our sample objects. We will also address critical questions related to phase curves for objects with albedo variations, multiple objects, or Centaurs/TNOs with potential ring system. Phase curves and H-magnitudes are crucial for the radiometric analysis of thermal data (e.g., Müller et al. [2017a] and references therein).

5.9. Others

It is also foreseen to develop various new tools, techniques, and services related to the above mentioned observing techniques, prediction tools and models. Our database(s) will also be made public towards the end of the SBNAF project in 2019. One possible long-term option is to merge our database(s) with exist-

ing services of the "Virtual European Solar and Planetary Access (VESPA[43])". The wealth of new lightcurve data obtained during SBNAF project will be made available to the public using widely used services like Strasbourg CDS and AL-CDEF, typically together with a scientific publication. In some cases the data will be shared with other projects, like the recetly accepted large proposal that plans to observe 38 large ($> 100\,\mathrm{km}$) MBAs with VLT/SPHERE[44] in high resolution (see Marsset et al. [2017]). Such large bodies are seen as primordial remnants of the early Solar System (Morbidelli et al. [2009]). The shape, size and spin reconstruction for these objects will benefit from the combination of Adaptive Optics images (from VLT/SPHERE), standard lightcurves, occultation, and thermal information. The derived volume (via their 3-D shape) together with mass estimates (mainly from Gaia) will allow us to determine their bulk density and hence to characterize their internal structure. This fundamental property is very relevant for addressing the questions regarding the earliest stages of planetesimal formation and their subsequent collisional and dynamical evolution.

6. Outlook

The core of the SBNAF project is to study selected small bodies at very different distances from the sun. We work on combining different observations and modelling techniques, knowing that very different approaches are required for NEAs, MBAs, Centaurs, or TNOs. Often we have to complement the analysis by pushing for more observations. A large and very important element of SBNAF is therefore the planning and conduction of measurements. At the same time, we develop new tools and services to combine information from ground and space, and also from very different observing techniques. It requires to extract

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[43]Virtual European Solar and Planetary Access database, see `http://www.europlanet-vespa.eu/`

[44]SPHERE is the extreme AO system and coronagraphic facility at the VLT; `https://www.eso.org/sci/facilities/paranal/instruments/sphere.html`

from each method the constraints for the derived object properties and also the reliability of these values. By focusing on objects with "ground truth" we will put the new tools on solid grounds. Our results are already partly available from our public webpage[45] and documented in more than 20 peer-reviewed (submitted, accepted and published) publications. More scientific publications, new tools, databases and various services for small-body observers can be expected during our 3-year project phase (until mid 2019).

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