1. PUBLISHABLE SUMMARY

Summary of the context and overall objectives of the project (For the final period, include the conclusions of the action)

The "Small Bodies Near and Far - SBNAF" project addressed critical points in the reconstruction of physical and thermal properties of near-Earth, main-belt, and trans-Neptunian objects. The aim was to better understand small bodies, their threat to our planet, and their possible role in the delivery of water and other organic materials that were necessary for life to develop on Earth.
Throughout SBNAF we conducted -and often coordinated- new observations with Kepler-K2, Hubble, ALMA, VLT, and numerous smaller telescopes around the world to obtain visible photometry to refine stellar occultation predictions, to observe these events, and to gather lightcurves. We combined lightcurve inversion, stellar occultations, thermophysical modelling, radiometric methods, and adaptive optics imaging to derived size, spin and shape, and thermal properties of our targets. The ground-truth information provided by space missions like Hayabusa2, OSIRIS-REx, NEAR-Shoemaker, Rosetta, DAWN allowed us to develop tools for the interpretation of space data and assess the limitations of each method.
The combination of methods and data from the ground and from astrophysics space missions (Herschel, Kepler-K2, Hubble, AKARI, Spitzer, etc.) improved our scientific understanding of selected targets and will enhance the future interpretation of much larger samples like (i) thousands of NEAs/MBAs (mostly) observed by WISE, (ii) the Spitzer and Herschel TNO catalogues, (iii) large MBAs for which Gaia will provide masses, or (iv) the well-characterized MBAs proposed as infrared calibration standards.

Work performed from the beginning of the project to the end of the period covered by the report and main results achieved so far (For the final period please include an overview of the results and their exploitation and dissemination)

The main results during the second reporting period (SRP; 04-2017 to 03-2019):
(1) The public ISAM service includes now shape models for more than 1600 asteroids (+3000 models in total). Models obtained by SBNAF have been published in several publications (Müller et al. 2017, Marsset et al. 2017, Marciniak et al. 2018, 2019). We updated D3.3 to evaluate newly available ADAM shape models by Viikinkoski et al. (2017) and Hanuš et al. (2018).
(2) The Gaia-GOSA service, an interactive tool to help amateur and professional observers plan their observations. It gathered more than 140 registered users and more than 500 uploaded observing nights featuring full lightcurves for more than 50 asteroids, mostly SBNAF targets from the Gaia-mass and calibrators lists.
(3) We added more than 170,000 observations to the public asteroid infrared database (IRDB: https://ird.konkoly.hu), including mid-IR/sub-mm measurements from IRAS, MSX, AKARI, WISE, and Herschel. We developed and verified procedures to colour-correct the data and added auxiliary parameters from the JPL/Horizons system for each IRDB entry. A web interface was developed and the IRDB was advertised during the workshop "Thermal Models of Planetary Science III". Operation of the IRDB is guaranteed at least until the end of 2021 thanks to support by Hungarian funding agencies.
(4) High-quality predictions for occultations covering 2017, 2018 and 2019 allow both amateur and professional astronomers to observe these scientifically important events. We obtained more than 25

successful TNO occultations from predictions with 10 mas accuracy, based on the Gaia Data Release 2 catalogue (April 2018). The orbit calculations for the moving targets included results from large observing campaigns conducted in Spain and affiliated observatories, often in close collaboration with the ERC Lucky Star project.
(5) SBNAF produced high-quality data products for small bodies' Herschel Space Observatory observations using sophisticated, Solar-System-specific data reduction and calibration schemes. The products and corresponding release notes were delivered to the Herschel Science Center to be uploaded to the Herschel Science Archive.
(6) We established a group of ~20 high-quality, well-characterised secondary asteroid calibrators with absolute flux predictions accurate on a 5-10% level at far-IR/submm/mm wavelengths covering a wide range of fluxes. These reliable model predictions support worldwide calibration activities for ground-, airborne-, and space-projects at mid-IR, far-IR, and sub-mm/mm wavelengths.
(7) Our focus was on synergy projects (several deliverables within WP6), which materialised in the many publications based on multiple techniques and datasets.

SBNAF's scientific results were presented in multiple international conferences and workshops, with 43 publicly available SBNAF abstracts for talks and posters and more than 30 additional workshop/ conference contributions during the SRP. A large fraction of the scientific outcome of our work is documented in publications in refereed journals: 53 published refereed publications (04/2017 to 03/2019), 10 accepted ones, and 4 recently submitted manuscripts. All of them include SBNAF results and/or have significant SBNAF individual/team contributions. The highlight of the SRP was the Nature paper by Ortiz et al. on "The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation", opening up a new avenue for planetary research.

We produced a wide range of outreach and educational material for the public. The most important scientific results are also connected to press releases, radio and TV interviews, podcasts, etc. which we listed in our public web page. The highlight in outreach was connected to the Nature paper with worldwide press coverage, countless public articles, talks, interviews and other outreach activities.

Progress beyond the state of the art, expected results until the end of the project and potential impacts (including the socio-economic impact and the wider societal implications of the project so far)

Our benchmark targets had often ground-truth information from interplanetary missions. This helped us to refine existing model techniques beyond the current state-of-the-art, to provide strategies for optimized observing campaigns at visual and thermal wavelengths, and to investigate the possibilities and limitations of current modelling techniques. This kind of ground-truth information is unique in astronomy and led to wide applications for objects without ground-truth information, and for various projects in the planetary community outside SBNAF. The SBNAF results are immediately available to the astronomical community, but also to many amateur astronomers, who provide substantial support for our project. Featuring in scientific publications, in turn, feedbacks into the amateur circles and creates and spurs further interest to get involved in these types of projects. This possibility of contributing to professional astronomy with affordable (and sometimes even sophisticated) amateur instrumentation is somewhat unique to our field, and the results of our small-body studies have captured great interest in the public. The socio-economic impact in the short term is difficult to trace and quantify, but SBNAF's tools and scientific results will surely contribute to the Basic Science demanded by the growing focus of Industry on the prospects of mining asteroids and what has been termed "in situ resource utilisation" (ISRU). In the shorter term, the occultation predictions and Gaia-

GOSA services are allowing amateur observers to actively further our knowledge of Small Bodies. These, along with other public outreach activities, broadens society's appreciation of Solar System small-body research.

Address (URL) of the project's public website

http://www.mpe.mpg.de/~tmueller/sbnaf/

Overview of the different techniques applied to minor bodies at different distances from the Sun.