AKARI and the 'Small Bodies: Near and Far' (SBNAF) project

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ABSTRACT

"Small Bodies: Near and Far" (SBNAF) is an EU Horizon2020-funded project with the aim of tackling critical points in the reconstruction of physical and thermal properties such as size, spin and shape, thermal inertia of small bodies of the Solar System, from trans-Neptunian objects to main-belt and near-Earth asteroids. Knowledge of our targets is maximised by the combination of several techniques which include light-curve inversion, stellar occultations or thermo-physical modelling. We apply these techniques to objects with ground-truth information from space missions (*Hayabusa, NEAR-Shoemaker, DAWN*, . . .) to assess their limitations and advance them beyond the state of the art. In particular, visible and thermal infrared data from the ground and space missions like *Herschel*, *Spitzer*, *Kepler-K2* and *AKARI* are crucial to understand the nature of small bodies.

SBNAF is also relevant for the operations and scientific exploitation of the *Hayabusa-2* mission —as it provided a physical characterisation of its target— and other sets of data. In addition, we build accurate thermo-physical asteroid models to establish new celestial calibrators for far infrared, mm and sub-mm projects and provide a connection to the *Herschel* and *Planck* high-quality calibration standards. Here we review our current progress and future work where the *AKARI* asteroid catalogue plays a very prominent role.

Keywords: Solar System and planetary formation

1. INTRODUCTION

Large asteroids, those with diameters larger than ~100 km, are thought to be primordial bodies that have escaped catastrophic disruption by collisions. Their shapes, rotational properties and bulk densities inform us about their internal structure and their collisional histories. These clues can therefore be used as constraints for early Solar System dynamical and collisional models that describe the conditions prevailing at phases such as planet formation and migration.

Most asteroids cannot be resolved by direct imaging from the Earth, which prevents us from inferring their shapes directly. This makes it difficult to estimate their volumes and hence their densities accurately. Ground-truth information has been obtained for very few small bodies from spacecraft, stellar occultations, or even adaptive optics, although some model assumptions are involved in the latter case. Thus, most shapes and rotational properties have been derived indirectly from optical light-curve inversion models instead. The convex-hull approximation (Kaasalainen & Torppa 2001), a necessary limitation to guarantee a mathematically unique solution, has yielded a few hundred asteroid shape models so far (for a review, see e.g., Ďurech et al. 2015).

Panel a in Figure 1 shows an example of the convex shape model of asteroid (9) Metis downloaded from the DAMIT data base (Ďurech et al. 2010, 2011). One of the many aims of SBNAF (Müller et al. 2017b) is to derive more realistic shapes for selected targets with SAGE (Bartczak et al. 2014, 2017), an algorithm that produces random mutations on a sphere until the optical light curves are fitted (hence its name *Shaping Asteroids with Genetic Evolution*). The model of (9) Metis derived from SAGE is shown in panels b and c of Figure 1. More realistic shapes will lead to more accurate volumes which, in combination with the masses of large main belt asteroids derived thanks to Gaia, will lead to more accurate densities.

2. *AKARI* IRC ASTEROID FLUXES AND THERMO-PHYSICAL MODELS

Thermo-physical models (TPMs; see e.g., Delbo et al. 2015, for a review) are used to calculate asteroid surface temperature distributions and observed fluxes. These depend on the size, shape, spin axis orientation of the body and thermal properties of the surface material such as albedo, thermal inertia (related to its thermal conductivity and porosity),

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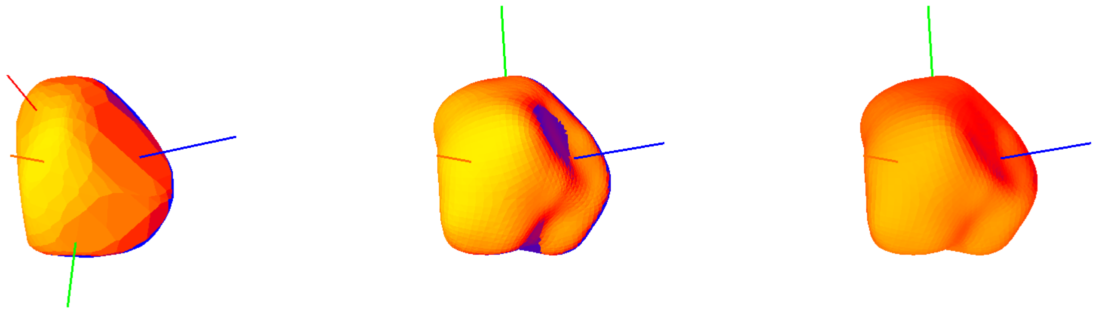

(a) (b) (c)

Figure 1. Sky views for the convex hull approximation (a) and SAGE (b and c) shape models of asteroid (9) Metis coloured as a function of temperature at an arbitrarily chosen epoch ($T_{\max} \approx 250$ K). The red, green, and blue lines indicate the orientation of the x, y, and z axes as would be seen by an Earth-based observer (North is upwards) if the body could be resolved. The orange axis points toward the sun. The models used for panels a and b assumed zero *thermal inertia* (in other words, no heat conduction toward the subsurface), whereas a thermal inertia of 75 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$ was assumed for panel c. The hottest areas in panel c are lower than in panel b because some energy is being transported into the subsurface as a consequence of the non-zero thermal inertia. On the other hand, the shadowed concave areas and the night-side are warmer in panel c because the heat absorbed at an earlier time is being conducted back to the surface.

or surface roughness (Figure 1). These model fluxes can be fitted to thermal infrared (IR) fluxes obtained from space observatories such as *AKARI* in order to constrain said thermal and physical properties of the small bodies' surfaces. Conversely, any shape model obtained from indirect methods (see Section 1) should reproduce all possible available information, including thermal IR data. This requirement is used to ensure and assess the quality and reliability of the shape and rotational models derived in the framework of SBNAF.

As the availability of accurate shape models increases, the combination of infrared data from several catalogues like *AKARI*, *WISE*/NEOWISE, or *Herschel* will significantly enhance our ability to physically and thermally characterise small bodies. For instance, recent work by Marciniak et al. (2017) combined *IRAS*, *AKARI*, and NEOWISE data in a thermo-physical analysis for the first time with shape models derived from SAGE. They produced more accurate diameters and albedos, and constrained thermal inertias of four asteroids with long rotational periods, which are underrepresented in our light-curve catalogues.

Meanwhile, we do not have constraints on the shape and rotational axes of most asteroids observed by the *AKARI* IRC catalogue, which total over five thousand objects, but in these cases it is possible to estimate the diameter with ∼10–20% accuracy assuming an idealised spherical model. Usui et al. (2011) and Hasegawa et al. (2013) produced diameters and albedos for the catalogue using a non-rotating sphere approximation. We have updated this catalogue with an upgraded version of the near-Earth asteroid thermal model (Harris 1998) implemented in Alí-Lagoa & Delbo' (2017) and discussed further expected applications for the *AKARI* IRC fluxes (Alí-Lagoa et al. submitted to Astronomy & Astrophysics).

3. PHYSICAL CHARACTERISATION OF THE *HAYABUSA* AND *HAYABUSA-2* TARGETS

AKARI data have played a major role in the characterisation of the thermal properties of JAXA's mission targets (25143) Itokawa and (162173) Ryugu (Figures 2 and 3). Müller et al. (2014a) obtained a high thermal inertia (700±200 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$) for Itokawa, which lead to an average grain size of 21^{+3}_{-13} mm, in agreement with *Hayabusa* in-situ observations (Yano et al. 2006; Kitazato et al. 2008). Müller et al. (2017a) also used *AKARI* data in combination with visible light curves to constrain the shape model and spin axis orientation and predict size, shape, rotational axis orientation, and thermal properties (albedo, surface roughness, thermal inertia) of Ryugu. They found a diameter between 810 and 905 m, visible geometric albedo between 0.044 and 0.05, thermal inertia of the top-most layer of 150–300 $\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, a very low surface roughness, and an average grain size between 1 and 10 mm. This model offers a fundamental baseline from which to develop operational scenarios for the mission and to interpret disc-resolved data taken from the spacecraft. Also, if these properties are confirmed in situ, such characterisation will constitute a fundamental benchmark for further thermo-physical studies.

4. FLUX CALIBRATORS

TPMs (Section 2) allow the prediction of precise fluxes at different wavelengths if accurate shape models, rotational and thermal properties of the asteroid are known. Models of large, relatively round asteroids have been successfully used as calibrators for missions such as *Herschel*, *AKARI* FIS, *ISO*, *Spitzer* MIPS (Müller et al. 2014b). The *AKARI* IRC data (Murakami et al. 2007; Onaka et al. 2007; Ishihara et al. 2010) combined with *Herschel* and other thermal IR

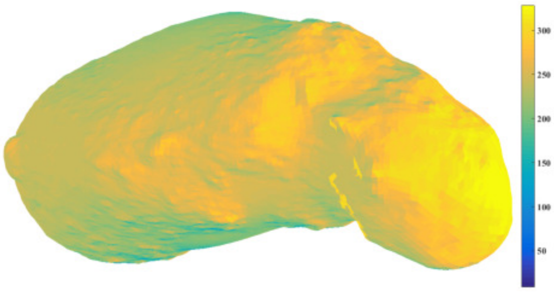

Figure 2. Sky view of *Hayabusa* target (25143) Itokawa as of 28 November 2017 coloured with the temperatures given by the thermo-physical model of Müller et al. (2014a).

(b) (a)

Figure 3. Sky view of *Hayabusa-2* target (162173) Ryugu as of 28 November 2017. The shape and rotational properties correspond to the model of Müller et al. (2017a). Left panel: zero thermal inertia and zero roughness idealised case. Right panel: best fit by Müller et al. with thermal inertia 200 J m^{-2} $s^{-1/2}$ K^{-1} and zero surface roughness. The maximum temperatures in each case are 343 K and 324 K (cf. Figure 1).

catalogues will allow us to infer thermal properties of our list of targets (see Section 1) with unprecedented information coverage. In turn, this will lead to improvements in the set of high-quality calibrators for *AKARI* FIS data, for instance. Our highly accurate far IR/submm/mm flux predictions for *Herschel*, ALMA, APEX, *SOFIA*, *ISO*, *AKARI*, IRAM, etc. can be accessed from the SBNAF public website http://www.mpe.mpg.de/~tmueller/sbnaf/results/bProducts.html.

5. SBNAF TOOLS AND SERVICES

Müller et al. (2017b) provide a summary of the structure of the SBNAF project. Additional detailed information including all scientific publications, tools, services, outreach events, or pedagogic material, can be found in our public website http://www.mpe.mpg.de/~tmueller/sbnaf/. Here we highlight some of our tools and services.

THE ISAM SERVICE (HTTP://ISAM.ASTRO.AMU.EDU.PL)

This web service (Marciniak et al. 2012) contains shape models and rotational properties for more than 900 asteroids collected from the literature. It allows the user to:

1. display the 3-D sky views of the asteroids at any chosen epoch
2. generate light curves
3. investigate viewing and illumination geometries.
4. animate the rotation and produce red-cyan stereoscopic images for 3-D visualisation.

GAIA-GOSA (HTTP://WWW.GAIAGOSA.EU)

Gaia-GOSA is an interactive tool supporting observers and amateurs in planning observational photometric campaigns. The asteroid prediction tool is based on the Gaia orbit and scanning law (ESA) and SSO ephemerides (MPC).

ASTEROID INFRARED DATABASE (IN PREPARATION)

A database of thermal IR/mm/sub-mm observations of small bodies (near-Earth asteroids, main-belt asteroids, trans-Neptunian objects, Centaurs) including ground-, airborne, and space-based observatories (*IRAS*, *MSX*, *AKARI*, *WISE*, *Spitzer*, *ISO*, *Herschel*, *Planck*) will be produced at a later stage by the SBNAF project. It will add optional useful ancillary information relevant to modellers, such as the procedure followed to produce colour-corrected fluxes such as those reported for the *AKARI* IRC catalogue (see e.g., Usui et al. 2011, or Hasegawa et al. 2013).

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REFERENCES

Alí-Lagoa, V., & Delbo', M. 2017, A&A, 603, A55
Bartczak, P., Michalowski, T., Santana-Ros, T., et al. 2014, MNRAS, 443, 1802B
Bartczak, P., Kryszczyńska, A., Dudziński, G., et al. 2017, MNRAS, 471, 941B
Delbo, M., Mueller, M., Emery, J. P., Rozitis, B., & Capria, M. T. 2015, Asteroids IV, 107
Ďurech, J., Sidorin, V., Kaasalainen, M. 2010, A&A, 513A, 46D
Ďurech, J., Kaasalainen, M., Herald, D., et al. 2011, Icarus, 214, 652
Ďurech, J., Carry, B., Delbo', M., et al. 2015, in Asteroids IV. Patrick Miche, Francesca E. DeMeo, and William Bottke (eds.) University of Arizona Press, Tucson, ISBN: 978-0-816-53213-1, p. 183-202.
Harris, A. W. 1998, Icarus, 131, 291
Hasegawa, S., Müller, T. G., Kuroda, D., et al. 2013, PASJ, 65, 34
Ishihara, D., Onaka, T., Kataza, H., et al. 2010, A&A, 514, A1
Kaasalainen, M., Torppa, J., 2001, Icarus, 153, 24K
Kitazato, K., Clark, B. E., Abe, M., et al. 2008 Icarus194, 137K
Marciniak, A., Bartczak, P., Santana-Ros, T., et al. 2012, A&A, 545A, 131M
Marciniak, A., Bartczak, P., Müller, T. G., et al. 2017, arXiv:1711.01893
Müller, T. G., Hasegawa, S., Usui, F., 2014a, PASJ, 66, 52M
Müller, T., Balog, Z., Nielbock, M. et al. 2014b, ExA, 37, 253M
Müller, T. G., Durech, J., Ishiguro, M., et al. 2017a, A&A, 599A, 103M
Müller, T. G., Marciniak, A., Kiss, C., et al. 2017b, arXiv:1710.09161
Murakami, H., Baba, H., Barthel, P., et al. 2007, PASJ, 59, S369
Onaka, T., Matsuhara, H., Wada, T., et al. 2007, PASJ, 59, S401
Usui, F., Kuroda, D., Müller, T. G., et al. 2011, PASJ, 63, 1117
Yano, H., Kubota, T., Miyamoto, H., et al. 2006, Science 312, 1350Y