Deliverable

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

Topic: COMPET-05-2015 - Scientific exploitation of astrophysics, comets, and planetary data

Project Title: Small Bodies Near and Far (SBNAF)

Proposal No: 687378 - SBNAF - RIA

Duration: Apr 1, 2016 - Mar 31, 2019

WP	**WP3, Lightcurve inversion technique**
Del.No	**D3.5**
Title	**Joint lightcurves and thermal models**
Lead Beneficiary	UAM
Nature	**Website, patents filling, etc.**
Dissemination Level	Public
Est. Del. Date	31 March 2018
Version	1.0
Date	April 3, 2018
Lead Author	Alí-Lagoa, V. (vali@mpe.mpg.de) MPE
Co-authors	Müller, T.G. (MPE), Marciniak, A. (AMU)

Objectives of WP: To join various types of data for full physical models of benchmark asteroids. To develop the web service with a database in order to provide the models to the community.

Description of deliverable

Joint lightcurve and thermal models. Nature: website, patents filling, etc.

Contents

1 Scope

The aim of this report is to document deliverable D3.5, which requires the publication of the shape models vetted against thermal infrared data and thermo-physical modelling featured in published (Müller et al. 2017; Marsset et al. 2017; Marciniak et al. 2018) as well as ongoing works. These models can be loaded at the ISAM service (Marciniak et al. 2012; see Table 1 for a summary about our usual acronyms), which offers a number of visualisation capabilities. An example of output produced by ISAM for one of these targets is given in Sec. 2, and more details can be found in Secs. 2 and 3 of deliverable D3.2.

We also take the opportunity of summarising and discussing in Sec. 3 the first peer-reviewed works (with SBNAF contribution) where visible light curves and thermal infrared (IR) emission data are modelled simultaneously to derive asteroid shape models, and we conclude with an outlook onto the remaining final year of the SBNAF project in this context in Sec. 4.

Acronym	Meaning	Input	Reference
ADAM	All-data asteroid modelling algorithm	VIS, AO, Occ	Viikinkoski et al. (2015)
CITPM	Convex-inversion thermo-physical model	VIS, IR	Ďurech et al. (2017)
ISAM	Interactive service for asteroid models	–	Marciniak et al. (2012)
KOALA	Knitted occultation, adaptive optics, and light-curve analysis	VIS, AO, Occ	Carry et al. (2010)
SAGE	Shaping asteroids using genetic evolution	VIS	Bartczak & Dudziński (2018)

Table 1: List of acronyms for the algorithms/tools used to obtain asteroid shapes and corresponding input data types. VIS: visible light curves. IR: (thermal) infrared data. AO: adaptive optics. Occ: stellar occultations.

2 Upload to the ISAM service

Shape models derived from SAGE, ADAM, and the CITPM and vetted against thermal models have been uploaded to the ISAM service. The following targets are included:

Target	Method	Reference
(6) Hebe	ADAM	Marsset et al. (2017)
(159) Aemilia	SAGE	Marciniak et al. (2018)
(227) Philosophia	SAGE	Marciniak et al. (2018)
(329) Svea	SAGE	Marciniak et al. (2018)
(478) Tergeste	SAGE	Marciniak et al. (2018)
(487) Venetia	SAGE	Marciniak et al. (2018)
(162173) Ryugu	CITPM	Müller et al. (2017)

Figure 1 shows sky projections of one of these targets at two selected dates and the corresponding predicted light curves. As detailed in Deliverable D3.2, there are additional visualisation capabilities, e.g. the user can produce animations of the rotation at a given epoch, obtain red-cyan anaglyphs of the sky views for 3-D visualisation, or simply "manually" inspect the shape model at any desired aspect angle. The shapes are also available for download in a standard format for further modelling.

3 Combined modelling of visible light curves and thermal infrared emission

Inversion of visible photometric light-curves to indirectly infer convex shapes of irregular small bodies and thermal/thermo-physical modelling of thermal infrared (IR) data have been introduced and discussed previously in deliverables D3.4 (Sec. 3), D6.1 (Sec. 2.2) and D6.5 (Sec. 3). Some more general background and references are available also in the SBNAF public website[1].

The KOALA (Carry et al. 2010) and ADAM (Viikinkoski et al. 2015) algorithms have used stellar occultations (SOs) and adaptive optics (AOs) in combination with optical light curves to derive non-convex shape models (including their corresponding rotational states) along with and absolute scale. Müller et al. (2017) and Ďurech et al. (2017) have shown that it is also possible to model thermal IR data simultaneously with optical light curves to derive absolutely-scaled, in some cases unique[2], *convex* shape models. These works are briefly summarised and discussed next.

3.1 "Asteroid shapes and thermal properties from combined optical and mid-infrared photometry inversion" (Ďurech et al. 2017)

This work shows the performance of the combined convex inversion of visible LC and thermal IR data applied to four main-belt asteroids as test cases. The algorithm has been called CITPM after *convex inversion thermo-physical model*. In a nutshell, the optical part is modelled using the Hapke parameters based on estimates from typical values, and reflectance spectra based on taxonomic class whenever available. On the other hand, the thermal component employed the Lagerros thermo-physical model accounting for thermal inertia and hemispherical-crater surface roughness. The usual Bond albedo (A) was replaced by the hemispherical albedo (A_h) self-consistently with the chosen set of Hapke parameters. The optimization of the fitting parameters minimised the total chi-square defined as:

$$\chi^2_{\text{tot}} = \chi^2_V + \omega\chi^2_T, \tag{1}$$

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[1] Available at `http://www.mpe.mpg.de/~tmueller/sbnaf/techniques/a_lightcurveinversion.html` and `http://www.mpe.mpg.de/~tmueller/sbnaf/techniques/b_radiometry.html`

[2] In contrast, pure light curve inversion often produces two mirror solutions.

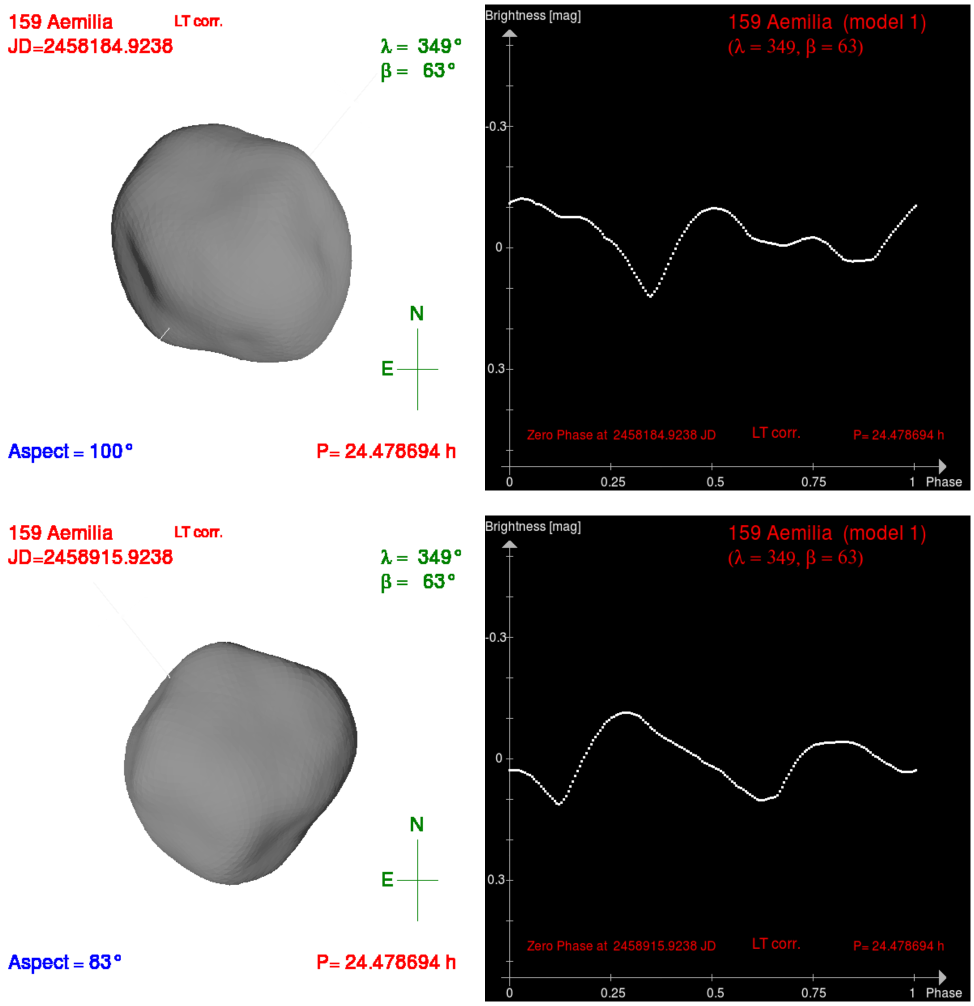

Figure 1: Left: Sky projections of asteroid (159) at March 7th 2018, 10:10:13 (JD=2458184.923773) and two years later (top and bottom, respectively). Right: corresponding predicted light curves.

where V stands for “Visible light curve”, T for “Thermal infrared”, and ω is a weight factor ensuring a balanced fitting of both parts.

The main benchmark target in this work is (21) Lutetia, chosen because of the ground-truth information produced by the Rosetta mission’s flyby. The CITPM produced a good-quality fit and very similar shape model as derived from the flyby. On the other hand, the best-fitting thermal inertia was higher than found in previous works, including those based on VIRTIS data (O’Rourke et al. 2012; Coradini et al. 2011; Keihm et al. 2012). Asteroid (2867) Steins was also featured based on the partial knowledge of its shape; however, this case proved to be less successful because of a more limited thermal IR coverage, which lead the CITPM to slightly overestimate the ground-truth diameter and produce a wider uncertainty range for the thermal inertia. Another illustrative case was (220) Stephania, for which the traditional LC inversion including sparse photometry did not lead to a unique solution but the CITPM did.

3.2 “Hayabusa-2 mission target asteroid 162173 Ryugu (1999 JU3): Searching for the object’s spin-axis orientation” (Müller et al. 2017)

Müller et al. (2017) also used the CITPM to model a rich set of visible light curves and thermal IR data simultaneously to derive a convex 3-D shape model with absolute scale and thermo-physical properties of the Hayabusa-2 target. The fitting procedure resulted in 11 possible pole solutions clustered in different parts of the sky, mostly Southern ecliptic coordinates. Three of these were considered more likely given their stability against the limit of inertia ratio. The final *reference solution* was chosen based on further and more detailed TPM analysis, leading to a spherical-equivalent diameter between 850 and 880 m, a relatively small thermal inertia between 150 and 300 $\mathrm{J\,m^{-2}s^{-1/2}K^{-1}}$, and an average grain size of 1–10 mm for the top layer of the surface material. This illustrated how the thermal data can help with cases in which the visible light-curve amplitudes are small.

On the other hand, the case of Ryugu was challenging for the CITPM because of the small amplitude of the light curves and limited quality of the data, so that further manual inspection and studies were required to discard less probable but statistically still possible solutions. The weight given to the different data types (visible vs. thermal, i.e. ω in Eq. 1) is also critical and requires further investigation.

4 Outlook and future work

Despite the great increase in availability of IR data in the last decade (AKARI, WISE, Spitzer, Herschel), these catalogues have not provided anything comparable to the archive of densely sampled optical light curves *for each object* accumulated over several decades. Thus, even though it has demonstrated some degree of success, combined (convex) inversion needs to be tested more extensively to understand all possible biases it may lead to in the more frequent cases where we do not have optimal and balanced data coverage and quality. To summarise, in order to ensure a high-quality scaled, rotational 3-D shape model we need

- high-quality and densely sampled visible light curves to fix the rotation period and constrain shape features
- that the light curves cover multiple apparitions/aspect angles to constrain the spin-axis orientation

- that the thermal data cover multiple aspect angles and wavelengths (this was discussed in deliverable D6.6). The different aspect angle coverage also puts constraints on the orientation of the spin axis in addition to the size and albedo, and thermal/thermo-physical properties require a good wavelength coverage.

These points underlie the different type of information afforded by the two classes of data: visible fluxes contain information strictly only about the illuminated parts of the surface, whereas non-illuminated parts can also contribute significantly to the IR fluxes. Said contribution depends on the thermal properties and prevailing temperatures, as the emission in the shorter wavelengths (or Wien part of the spectrum) is dominated by the hotter terrains and the entire projected area of the body is connected more to the longer wavelengths.

Finally, the possibility of obtaining non-convex shapes from simultaneous inversion remains unexplored. Critically hindered by a delay of over a year in the acquisition of the necessary computer cluster at AMU, we concluded that testing this approach with SAGE is an unrealistic goal to be fully completed within the remaining year of SBNAF. Thus, we will continue our usual method of testing the new state-of-the-art shape models (from both SAGE and ADAM) whenever possible, and convex ones otherwise, against the thermal data. These will still constitute strong constraints to assess the reliability of the shape and rotational models, whatever the method used to derive them. Another important byproduct is the possibility to robustly predict thermal infrared and sub-mm and mm fluxes for calibration of astronomical instrumentation. This is the topic of work package 4, which will expand the list of secondary calibrators based also on this work (e.g. Juno, Cybele, featured in the table below).

Currently, we are involved in several works in this context, including the following targets:

Target	Method	References
(2) Pallas	ADAM	Hanus et al. (2017)
(2) Pallas	SAGE	In preparation
(3) Juno	ADAM	Hanus et al. (2017)
(8) Flora	ADAM	Hanus et al. (2017)
(9) Metis	ADAM	Hanus et al. (2017)
(9) Metis	SAGE	Bartczak & Dudziński (2018)
(10) Hygiea	ADAM	Hanus et al. (2017)
(21) Lutetia	SAGE	In preparation
(65) Cybele	ADAM	Viikinkoski et al. (2017)
(24) Themis	ADAM	Viikinkoski et al. (2017)

SAGE models for these and other targets to be completed within the project will be likewise uploaded to the ISAM service as soon as the connected peer-reviewed publications are accepted.

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