Deliverable D4.6

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

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Lead Author	T. Müller, MPE (tmueller@mpe.mpg.de)
Co-authors	A. Marciniak, AMU

Objectives of the WP: To transport the space-based (Herschel, Planck, Akari) calibration to ground-based and airborne infrared, submm, and millimetre projects with a high demand for asteroids as calibrators.

The immediate goals of delivery (D4.6) are:

- collecting the calibration needs and requirements of ongoing and future far-IR, submm, mm projects
- study of many large main-belt asteroids for their potential use as secondary calibrators with the focus on collection of available object information and thermal IR observations (“D3.3 Shape and spin solutions for secondary calibrators” has the focus on the required work related to lightcurves and visual observations in general; “D5.2 High-precision photometry measurement table” provided the necessary model input for absolute magnitudes and slope parameters)
- establishment of criteria for a final selection of secondary asteroid calibrators

Contents

1 Introduction

The goal of WP4 Asteroid-related calibration is to establish a set of high-quality celestial calibrators for far-IR, submm, and mm projects (ground, air-borne, and space). See also descriptions in Deliverables:

- D4.1 Observation summary table (30 Apr 2016)[1]
- D4.2 Submm/mm model predictions & gzipped tar file with model v0 predictions for 20 asteroids for period 2016-2020 (30 Jun 2016)[2], mainly for observation planning purposes (labeled as model version 0)
- D4.3 Calibration asteroid model predictions (30 Sep 2016)[3], for direct calibration applications

and related deliverables:

- D3.3 Shape & Spin solutions for secondary calibrators (31 Mar 2017)
- D5.4 High-precision photometry measurement table (30 Sep 2016)
- D6.2 Shape & spin solution for primary calibrators (09 Dec 2016)
- D6.3 In-situ object properties (31 Dec 2016)
- D6.5 "Ground truth" shape models (31 Mar 2017)
- D6.8 3D shape models for large MBAs (30 Sep 2018)

available either on our password-protected internal web page[4] on our public web page[5].

The work started already in the mid '90s in preparation for the Infrared Space Observatory (ISO) and continued during the last two decades in the context of various ground, airborne and space projects, mainly to cover the calibration needs at far-IR, but recently also at submm/mm wavelengths.

2 Calibration needs of ongoing and future far-IR, submm, mm projects

The large and bright main-belt asteroids fill the flux gap between the sub-mm/mm calibrators Mars, Uranus and Neptune, and the mid-IR bright calibration stars (see Fig. 1 in D4.1). They allow to interconnect different worlds of calibrators. The diurnal and seasonal flux changes of asteroids are understood and predictable with high accuracy. The thermal emission spectra are featureless (with exception of very shallow, low-level, broad emission features at MIR wavelengths) and the shapes of the spectral energy distributions are known. There are also other secondary calibrators existing (e.g. Siringo et al. 2009), but many show variability, are spatially extended, or have significant spectral structures.

[1] http://www.mpe.mpg.de/~tmueller/sbnaf/results/SBNAF_deliverable_D4_1.pdf
[2] http://www.mpe.mpg.de/~tmueller/sbnaf/results/SBNAF_deliverable_D4_2.pdf
[3] http://www.mpe.mpg.de/~tmueller/sbnaf/results/SBNAF_deliverable_D4_3_v1.pdf
[4] http://www.mpe.mpg.de/~tmueller/SBNAF/DELIVERABLES/deliverables.html
[5] http://www.mpe.mpg.de/~tmueller/sbnaf/

Asteroids are typically used for very different calibration purposes, including pointing and tracking tests, absolute flux calibration, detector linearity tests, searching for filter leaks, determination of the relative spectral response function, observing mode validation, cross-calibration aspects, detection of possible instrument performance degradations, and many other calibration tasks where bright point-sources with reliable flux predictions are needed (see also Müller et al. 2014).

For MIR instruments which traditionally use stars as prime calibrators, the asteroids provide means to test the detector linearity up to the detector saturation limits. At the same time, they are crucial for verifying filter transmission curves and for the search for filter leaks (MIR-bright asteroids are faint at NIR while stars of similar MIR brightness are extremely bright at NIR).

Submm/mm instruments use planets (Mars, Uranus, Neptune) as prime calibrators (see also Müller et al. 2016 and references therein). Here, the asteroids are useful to go to fainter flux levels, they are much smaller in apparent size (all are well below $1''$), and they are more numerous, which means there are always a few available for observations at any given time. In addition, their fluxes and flux changes are predictable via thermophysical models.

Thus, the needs of MIR/FIR airborne and space projects, or ground-based submm/mm projects are:

- to provide a sufficient number (20-50) of calibration asteroids to have always a few available at any given time
- to bridge the flux gap between prime calibrators Uranus & Neptune (several hundred Jansky in the submm) down to the fiducial stars (below 1 Jansky in the submm); if possible also going down to levels below 100 mJy.
- to provide reliable model predictions in the wavelength range from MIR (around $10\,\mu$m) to the mm-range
- to provide model solutions with absolute flux accuracies of better than 5% (prime calibrators) and in the range 5-10% (secondary calibrators) for flux/amplitude calibration
- to provide objects with high-quality SEDs for spectral calibration work

3 Target selection and availability of relevant information/observations

We have established the following requirements for selecting asteroids as potential calibrators:

- Intermediate to large main-belt asteroids without satellites (or very small satellites with negligible contributions at thermal IR wavelengths)
- Objects with known shape and spin information, with no signs of albedo variegation, based on rich datasets of dense, high quality lightcurves, avoiding objects with

large-amplitude or exotic lightcurves (see "D3.3 Shape & spin solutions for secondary calibrators")

- Availability of high-quality, multi-epoch, multi-wavelength thermal data (see Table 1)
- Availability of high-quality absolute magnitudes and phase slopes (see "D5.4 High-precision photometry measurement table")
- if possible, availability of occultation and/or AO imaging data and/or "ground truth" from interplanetary missions (information on some potentially relevant targets are given in D6.5)

We found 29 potential secondary calibrators following these criteria. Table 1 provides an overview with the available key thermal IR data.

The IRAS measurements are taken from Tedesco et al. (2002a), the four IRAS bands are at 12, 25, 60, and 100 μm (N×4 means that there are N epochs, each with a full 4-band detection). The MSX data are given in Tedesco et al. (2002b), the four MSX bands are at 8.28, 12.13, 14.65, and 21.34 μm (N×4 means that there are N epochs, each with a full 4-band detection). The AKARI-IRC data[6] were presented in Usui et al. (2011), the AKARI-IRC bands for the all-sky survey were S9W and L18W, with effective wavelengths at 9.0 and 18.0 μm (N/M in Table 1 means N independent detections in S9W and M detections in L18W). The WISE W3 and W4 data can be extracted from the IPACS IRSA service[7] (Mainzer et al. 2011). The crucial WISE data are related to the W3 (11.1 μm) and W4 (22.6 μm). Here, we included WISE data which are either unsaturated or only partially saturated (less than 1.0 mag). N/M in the table give the number of useful W3 detections (N) and the number of W4 detections (M). The Herschel measurements are available from the Herschel Science Archive (HSA[8]), the Herschel-PACS bands are at 70, 100, and 160 μm (Poglitsch et al. 2010), with two bands taken in parallel (either 70 & 160 μm or 100 & 160 μm); the Herschel-SPIRE bands are at 250, 350, and 500 μm (Griffin et al. 2010) and all three bands are taken simulataneously. ISO: see Dotto et al. (2002); Spitzer: either MIPS (Stansberry et al. 2007) or IRAC lightcurve measurements (Bhattacharya et al. 2008); SOFIA/ALMA: data from calibration programmes; mir: groundbased data at MIR (VLT-VISIR, VLT-TIMMI/2, SUBARU-Comics, pre-IRAS, etc.), submm (APEX, CSO, JCMT-UKT14,-SCUBA/2, etc.), or at mm wavelengths (ATCA, IRAM, etc.). Planck fluxes are given in Planck 2013 results. XIV. Zodiacal emission (Planck Collaboration 2013). The Rosetta-MIRO data are presented in Gulkis et al. (2012). Our collection in Table 1 is certainly not complete and not all listed measurements are published, but most of these measurements will be available for our work on asteroidal calibration standards.

For our purposes, it is important to have multiple datasets from different missions available. Data should also cover a significant wavelength range and many different observing geometries (helio-centric distances, phase angles, aspect angles, rotational phases).

[6] `http://www.ir.isas.jaxa.jp/AKARI/Archive/Catalogues/Asteroid_Flux_V1/`
[7] `http://irsa.ipac.caltech.edu/Missions/wise.html`
[8] `http://archives.esac.esa.int/hsa/whsa/`

Num	Asteroid Name	IRAS 4-band	MSX 4-band	AKARI 9/18	WISE W3/W4	Herschel-PACS chop-nod	Herschel-PACS scan-map	-SPIRE 3-band	other	remarks
1	Ceres	Müller et al. 2014, ExpAstron 37, 253							ALMA, APEX, Planck	Primary
2	Pallas	Müller et al. 2014, ExpAstron 37, 253							ALMA, APEX, Planck	Primary
4	Vesta	Müller et al. 2014, ExpAstron 37, 253							ALMA, APEX, Planck	Primary
21	Lutetia	Müller et al. 2014, ExpAstron 37, 253							Rosetta-MIRO	Primary
3	Juno	8×4	—	4/4	-/-	6/6/12	12/12/24	22×3	ISO,Spitzer,SOFIA, Planck,mir/submm/mm	ALMA-resolved high-quality secondary
6	Hebe	Marsset et al. 2017, A&A submitted						17×3	ISO,Spitzer,AO,Planck	high-quality secondary
7	Iris	6×4	—	3/4	-/-	-/-/-	-/-/-	7×3	Spitzer, mir	under discussion
8	Flora	7×4	—	4/6	-/-	5/4/9	8/8/16	8×3	mir,Planck	good thermal dataset
9	Metis	—	1×4	4/3	-/-	-/-/-	-/-/-	—	ISO,Planck, mir/submm/mm	poor thermal dataset
10	Hygiea	9×4	—	3/3	-/-	6/5/11	12/8/20	21×3	ISO,Planck, mir/submm/mm	rich thermal dataset
12	Victoria	2×4	—	3/2	-/-	-/-/-	-/-/-	—	Spitzer,Planck, mir	poor thermal dataset
18	Melpomene	5×4	—	3/3	-/-	1/0/1	1/0/1	—	Spitzer,Planck, mir	poor thermal dataset
19	Fortuna	—	—	3/3	-/-	1/1/2	2/0/2	41×3	Spitzer,Planck, mir	under discussion
20	Massalia	3×4	—	6/6	-/-	4/4/8	8/8/16	5×3	ISO,Spitzer,Planck, mir	good thermal dataset
23	Thalia	6×4	1×4	1/3	-/-	-/-/-	-/-/-	—	Spitzer, mir	under discussion
24	Themis	—	—	4/4	-/-	-/-/-	-/-/-	—	mir	poor thermal dataset
29	Amphitrite	4×4	—	3/4	0/10	1/1/2	2/2/4	6×3	Planck, mir/submm	good thermal dataset
37	Fides	8×4	—	3/3	-/-	-/-/-	-/-/-	7×3	mir	poor thermal dataset
40	Harmonia	7×4	—	3/5	0/12	-/-/-	-/-/-	5×3	Spitzer, mir	under discussion
47	Aglaja	7×4	—	2/1	0/26	1/1/2	4/4/8	7×3	mir	good thermal dataset
52	Europa	7×4	—	4/3	-/-	5/5/10	12/12/24	14×3	ISO,Planck, mir/submm	rich thermal dataset
54	Alexandra	5×4	—	3/5	-/-	-/-/-	2/2/4	8×3	ISO, mir	under discussion
65	Cybele	6×4	—	4/2	-/-	2/2/4	6/6/12	11×3	ISO,ALMA, mir/submm	rich thermal dataset
88	Thisbe	2×4	—	3/4	-/-	3/3/6	8/8/16	11×3	Planck,	rich thermal dataset
93	Minerva	2×4	2×4	3/3	-/-	-/-/-	2/2/4	6×3	Spitzer	under discussion
173	Ino	5×4	—	3/1	-/-	-/-/-	-/-/-	9×3		poor thermal dataset
360	Carlova	6×4	—	4/4	0/26	2/2/4	-/-/-	—	mir	under discussion
372	Palma	6×4	—	2/4	15/15	-/-/-	-/-/-	5×3		under discussion
423	Diotima	3×4	—	5/1	0/12	1/1/2	2/2/4	—	mir/submm	under discussion
471	Papagena	4×4	—	3/3	-/-	-/-/-	-/-/-	—	Spitzer	poor thermal dataset
511	Davida	8×4	—	4/3	0/36	-/-/-	2/2/4	8×3	ISO,Planck, mir	under discussion
532	Herculina	6×4	—	4/2	-/-	-/-/-	-/-/-	—	ISO, mir/submm/mm	poor thermal dataset
704	Interamnia	10×4	—	7/4	-/-	3/3/6	10/10/20	10×3	Planck, mir	good thermal dataset

Table 1: Potential secondary calibrators: statistics on the availability of thermal measurements (not complete). More information on the columns and entries is given in the text.

4 Steps towards secondary asteroid calibrators

For the establishment of secondary asteroid calibrators there are several necessary steps:

- extract useful thermal observations (IRAS, MSX, AKARI, WISE, Herschel, submm/mm from APEX, IRAM, ALMA, Planck, SOFIA, ground-based MIR, etc.): these data are currently prepared for our SBNAF IR database (D2.5 & D2.6)
- setup of shape & spin models: in most cases convex solutions (DAMIT database or updated solutions from AMU); non-convex (ADAM, KOALA or SAGE) solutions for objects with clear indications for non-convex structures and for cases where the non-convex solutions are superior to convex solutions.
- testing of convex and non-convex solutions against all thermal data (in parallel to spherical shapes) to quantitatively assess their quality as calibrators based on how well they reproduce the thermal data.
- run radiometric techniques for size/albedo/TI/roughness determination, similar to work done on Hebe (Marsset et al, in preparation), Lutetia (O'Rourke et al. 2012), Aemilia (Marciniak et al., in preparation), and several other MBAs (see also papers listed in "D5.6 Observational publications 1")
- extensive testing of the shape/spin model in combination with the new radiometric solutions: (i) are all thermal data explained? (ii) how well are all available lightcurves fitted? (iii) is the shape/spin solution unique? (iv) can the radiometric size and the shape silhouette be confirmed by good-quality multi-chord occultation events? (v) or by comparison with AO images?
- characterization of the final model quality, accuracy of flux predictions in different wavelengths regimes (MIR, FIR, submm, mm), statistics on daily and annual variability, known issues (satellites, submm/mm emissivity, activity, strange findings, unexplained data, etc.)
- placing the final model solution (absolute scaled model solutions with full header information on size, albedo, thermal properties) in the ISAM web service (http://isam.astro.amu.edu.pl/) to make it publicly available
- produce flux predictions at key MIR, submm/mm wavelengths, with sufficient time resolution (10 min? 30 min? or 1 hour?) for the next years for direct calibration applications and make them publicly available on the SBNAF page[9].

In addition, the following steps are still necessary:

- Consolidation of the H-G values for each object (following up on discussions in Pravec et al. 2012): discussions have started and will be continued in future SBNAF team meetings, including also external experts.
- Feeding all (reliable & well-calibrated) thermal measurements into our SBNAF-internal IR database (ongoing work)

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

- Final calculation of colour-corrected mono-chromatic flux densities for all thermal measurements (taking into account the relevant calibration conventions, the filter curves, and the selection of the final reference wavelengths)
- Establishing of improved shape & spin solutions for targets where recent lightcurves were taken
- Testing of shape/spin solutions & selection of the best solutions in the radiometric sense
- Proper radiometric testing (as it was done for our primary calibrators by Müller et al. 2014; or in support for the work by Marsset et al. 2017).
- Careful test of applicability of submm/mm emission models against Herschel-SPIRE, ALMA, APEX, IRAM, and Planck data
- Specific test of applicability of radiometric model solutions for epochs where a given object was very close to pole-on viewing geometry
- Regular contact and discussions with calibration experts at various observatories (ALMA, APEX, SOFIA, IRAM, etc.).
- Documentation of the work

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