Deliverable

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

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WP	**WP4 Asteroid-related calibration**
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WP4 Asteroid-related calibration
Objectives: 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.

Description of deliverable D4.1
Summary table with existing and missing information & observational data

Description of deliverable

I. Introduction

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

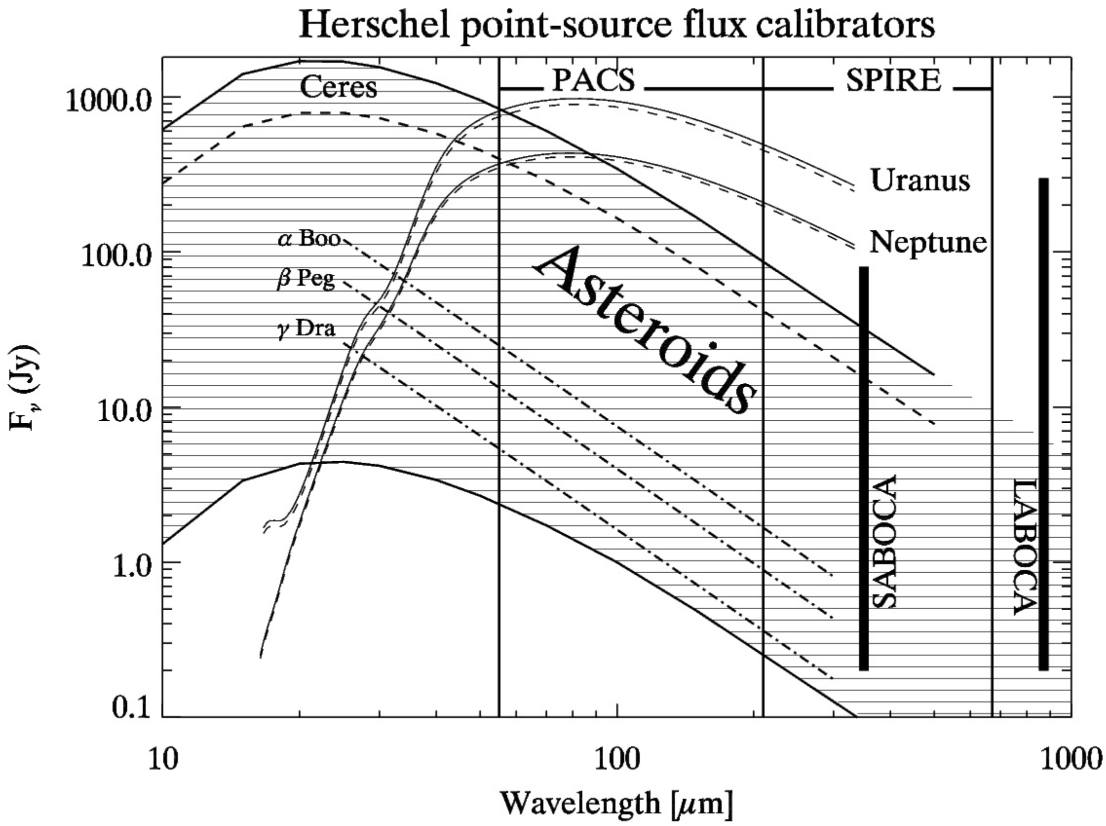

Fig 1: *The spectral energy distributions of the brightest calibration stars (used at mid-IR wavelengths), Uranus/Neptune (used often at submm/mm wavelengths) and the shaded area which is covered by a few large and well-known asteroids. The Herschel-PACS and SPIRE ranges are shown, as well as APEX SABOCA/LABOCA bands and typical flux ranges. Asteroids bridge between stars and planets, between mid-IR and submm/mm, and between space and ground-based calibration worlds.*

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. But not all asteroids are known equally well, models reach different quality levels, and the applicability for specific calibration goals is limited. The goal of SBNAF WP4 is to collect observational data, as well as model-relevant aspects (i) to improve the characterization of large main-belt asteroids in the calibration context; (ii) to reach a better model quality for different far-IR/submm/mm calibration purposes; (iii) to document the status, progress, applicability, and limits in using asteroids as calibrators for astronomical projects; (iv) to provide ready-to-use calibration products to different observatories in the world (Herschel, Alma, Sofia, APEX, LMT, IRAM, etc.).

II. Background

With the availability of the full thermal infrared (IR) wavelength range (from a few microns to the millimetre range) through balloon, airborne and space-borne instruments, it became necessary to establish new calibration standards and to develop new calibration strategies. Instruments working at mm-/cm-wavelengths were mainly calibrated against the planets Mars, Uranus and Neptune, while the mid-IR range was always tied to stellar models (see references in Müller et al. 2014, ExpAstron 37, 253). For the far-IR/sub-mm regime no optimal calibrators were available right from the beginning: the stars are often too faint for calibration aspects which require high signal-to-noise (S/N) ratios or are problematic in case of near-IR filter leaks. The planets are very bright and not point-like anymore. They are causing saturation or detector non-linearity effects. Between these two types of calibrators there remained a gap of more than two orders of magnitude in flux. This gap can be filled by large, well-known and well-characterized main-belt asteroids and their corresponding model predictions.

The idea of using asteroids for calibration purposes goes back to IRAS (Beichman et al. 1988, IRAS Exp. Suppl.). The IRAS 12, 25 and 60 μm bands were calibrated via stellar models and in that way connected to ground-based N- and Q-band measurements. But at 100 μm neither stellar model extrapolations nor planet models were considered reliable. Asteroids solved the problem. Models for a selected sample of large main-belt asteroids were used to "transfer" the observed IRAS 60 μm fluxes out to 100 μm and calibrate in that way the IRAS 100 μm band.

There was an independent attempt to establish a set of secondary calibrators at sub-millimetre (sub-mm) wavelengths to fill the gap between stars and planets. Ultra-Compact H-II regions, proto-stars, proto-planetary nebulae and AGB-stars were selected, but often these sources are embedded in dust clouds which produce a strong and sometimes variable background. The modelling proves to be difficult and accurate far-IR extrapolations are almost impossible.

The Infrared Space Observatory (ISO) was also lacking reliable photometric standards at far-IR wavelength (50–250 μm) in the flux regime between the stars and the planetary calibrators Uranus and Neptune. Müller & Lagerros 1998 (A&A 338, 340) provided a set of 10 asteroids, based on a previously developed thermo-physical model code by Lagerros (1996, 1997, 1998, A&A). These sources have been extensively observed by ISO for the far-IR photometric calibration, for testing relative spectral response functions and for many technical instrument and satellite purposes.

AKARI followed the same route to calibrate the Far-Infrared Surveyor (FIS) via stars, asteroids and planets in the wavelengths regime 50–200 μm (Kawada et al. 2007, PASJ 59; Shirahata et al. 2009, PASJ 61). The Spitzer mission considered in the beginning only stars for calibration purposes. But due to a near-IR filter leak of the MIPS 160 μm band, the calibration scientists were forced to establish and verify calibration aspects by using cooler objects. The asteroids served as reference for the flux calibration of the 160 μm band as well as for testing the non-linear MIPS detector behavior (Stansberry et al. 2007, PASP 119).

In preparation for Herschel and ALMA a dedicated asteroid program was established (Müller 2005, ESA-SP 577, 471). This led to a sample of about 50 asteroids for various calibration purposes. Along the mission, only the 12 asteroids with presumably the highest quality characterization were repeatedly observed for calibration purposes.

III. Lists with large main-belt asteroids for calibration purposes

Following up on the successful usage of asteroids as calibrators for Herschel, a list with 20 asteroids was established to support on-going and future ground-based and airborne project, mainly for planning of calibration applications:

- Asteroids: (1) Ceres, (2) Pallas, (3) Juno, (4) Vesta, (6) Hebe, (7) Iris, (8) Flora, (9) Metis, (10) Hygiea, (12) Victoria, (19) Fortuna, (23) Thalia, (29) Amphitrite, (52) Europa, (54) Alexandra, (88) Thisbe, (471) Papagena, (511) Davida, (532) Herculina, (704) Interamnia
- Provided to ALMA, APEX, IRAM, LMT, SOFIA, ... for calibration purposes, with predictions at agreed wavelengths and frequencies, covering the next 5-10 years into the future
- Models (simple Standard Thermal Model predictions) include the changing observing geometry (seasonal changes), but not the daily changes due to the object's rotation, nor the thermal effects or emissivity changes with wavelengths
- Model prediction are accurate on a 10-30% level, depending on object, and observing geometry
- **Model version 0.0** (--> for planning purposes only!)

A sub-list with Herschel's best 12 calibration asteroids was defined in May 2011:

- (1) Ceres, (2) Pallas, (3) Juno, (4) Vesta, (6) Hebe, (8) Flora, (10) Hygiea, (20) Massalia, (21) Lutetia, (52) Europa, (88) Thisbe, (704) Interamnia
- Based on Herschel (PACS/SPIRE) calibration plans and including checks against other data from ground (mid-IR/submm/mm) and space (IRAS, ISO, MSX, Spitzer, Akari)
- To be provided to ALMA, APEX, IRAM, LMT, SOFIA, ... for calibration purposes, with predictions at requested wavelengths and frequencies, calculated exactly for the corresponding observing epoch (after observations have been executed) or, alternatively, with predictions in a 10-min sampling interval to cover seasonal and rotational flux changes
- To be linked in the Herschel Science Archive (HSA) to all Herschel-PACS/SPIRE/HIFI observations of these asteroids, considering the true

observing and illumination geometry, one model prediction per OBSID, in agreed FITS format
- Model predictions (full thermo-physical models TPM, including shape models, rotation properties, thermal surface properties, true size and albedo values, etc.) were partially tested against multiple Herschel (PACS/SPIRE) observations
- Model prediction are accurate on a 5-10% level, depending on object, and observing geometry
- **Model version 1.0** (--> for basic calibration purposes)

Four large main-belt asteroids as prime calibrators
- (1) Ceres, (2) Pallas, (4) Vesta, (21) Lutetia
- Documented in Müller et al. 2014, ExpAstron 37, 253: Herschel celestial calibration sources: Four large main-belt asteroids as prime flux calibrators for the far-IR/sub-mm range
- To be linked in the Herschel Science Archive (HSA) to all Herschel-PACS/SPIRE/HIFI observations of these four asteroids, considering the true observing and illumination geometry, one model prediction per OBSID, in agreed FITS format (overwriting model version 1.0)
- Model predictions (full thermo-physical models TPM, including shape models, rotation properties, thermal surface properties, true size and albedo values, etc.) were fully tested against multiple Herschel (PACS/SPIRE) observations
- Model prediction are accurate on a 5% level
- **Model version 2.0** (--> for high-quality absolute calibration purposes!)

IV. Shape and spin-vector quality information

As part of the SBNAF (WP4) we plan to set up the highest possible model solutions for a range of asteroids for potential calibration applications. One important part of this work is the determination of highly reliable shape and spin-vector solutions for each asteroid. This work requires to collect all existing light curves (from publications, from data bases, from own archives), but also to re-observe light-curves whenever necessary. State-of-the-art light-curve inversion techniques lead then to (i) the determination of the rotation period; (ii) the construction of shape solutions (convex and non-convex shape); and, (iii) solutions for the spin-axis orientation. Auxiliary data (from occultations, direct imaging from HST, AO techniques, interplanetary missions, etc.) can help in some cases to refine these model solutions. With the availability of more and new data the solutions sometimes change, but in the following table we try to summarize the current status after the first month of SBNAF-dedicated investigations. In parallel, we plan and conduct new measurements – mainly light-curve measurements and occultation events – to improve the model solutions for problematic objects or for those which were not observed for many years.

	[1]	[2]	[3]	[4]	[5]
19 Fortuna	3	a1	4	A	C
511 Davida	3	a1	4	A	C
3 Juno	3	a1	3	A	C
88 Thisbe	3	a1	3	A	C
29 Amphitrite	3	a1	3	A	C
93 Minerva	3	a2	3	A	B
40 Hamonia	3	a1	2	A	C
54 Alexandra	3	a1	2	A	C
52 Europa	3	b	4	A	B
704 Interamnia	3		2	A	E
6 Hebe	3	b	3	A	B
65 Cybele	3		2	A	E
423 Diotima	3	a1	3	A	C
37 Fides	3	a1	3	A	C
7 Iris	3	c	2+	B	C
8 Flora	3	c	3	B/A	C
10 Hygea	3	c	3	B/A	C
20 Massalia	3	c	2	B	D
372 Palma	3	c	3-	B	D
18 Melpomene	3	a1	3	A	C
360 Carlova	3	c	2+	B	D
47 Aglaja	3			B	E
173 Ino	3		2	C/D	C

Low Uncertainty High Uncertainty

Explanations

(1) Synodic period (low precision) determination quality code from LCDB "Asteroid Lightcurve Database" (Warner, Harris, Pravec 2009, Icarus 202, 134. Updated December 2014). "3" - secure solution, no ambiguity.

(2) DAMIT (model solution at http://astro.troja.mff.cuni.cz/projects/asteroids3D/web.php (a1 - unique convex solution; a2 - unique non-convex solution; b - similar convex and non-convex solution; c - two convex solutions).

(3) Quality code of best spin axis solution (source: LCDB). The Q value gives our assessment of the quality of the pole solution and closely parallels the U rating assigned to light curves.
0 - Later proven to be wrong.
1 - May be completely wrong.
2 - Good determination, pole likely correct to 15-20°, but may be ambiguous with two or more solutions that are possible, or the sense of rotation is not determined.

3 - Reliable determination of both spin axis direction and sense of rotation, i.e., prograde or retrograde.
4 - Reliable determination. Same as Q = 3 but a shape model has been determined by inversion, AO, or radar, or ambiguous models have been eliminated by occultation profile matching.

(4) Poznan team quality codes for spin axis and sidereal (high precision) period solution:
A - Objects with a unique spin solution, no matter the shape model
B - Objects with two solutions with a mirror-pole ambiguity, which could be ruled out with a single additional observation (thermal, adaptive optics, stellar occultation, radar, etc.).
C - Asteroids with multiple pole solutions (observations needed for other geometries to constrain the model)
D - Asteroids with multiple spin state solutions (in particular, multiple sidereal period solutions).

(5) Poznan team quality codes for shape models:
A - Asteroids with detailed up to a small-scale shape model (high resolution models from in situ imaging)
B - Asteroids with a medium-scale shape details (a non-convex model which converges with the convex solution)
C - A first-order shape model, like a unique convex solution, based on dense light-curves
D - A low-resolution first-order ("angular") shape model based on mainly sparse data or on limited dense data
E - A tri-axial ellipsoid unique shape model

V. Information about key thermal IR observations

Thermal measurements are key to determine the size, albedo and thermal properties of an asteroid. If shape and spin properties are already known, then the thermal measurements allow to scale these shape models to physical units. Auxiliary data (from occultations, direct imaging from HST, AO techniques, interplanetary missions, etc.) can help in some cases to refine the radiometric size-albedo-thermal solutions. Important measurements in this context are space mid-/far-IR measurements from IRAS, ISO, MSX, Akari, Herschel, but also from Spitzer or Wise when available. Testing model at submm/mm wavelengths is also a critical element in verifying model solutions and to investigate at which wavelenths sub-surface emission starts to play a significant role. In the following table we tried to summarize crucial available and calibrated measurements for our potential calibrators. Many of the bright main-belt asteroids suffer from strong saturation and/or non-linearity effects in Spitzer or Wise measurements (not included here). The meaning of the abbreviations: y: yes, n: no; PP: PacsPhoto; PS: PacsSpectro; SP: SpirePhoto; H: HIFI observing modes; available ground-based submm/mm observations are mainly from calibration programmes of ALMA, ATCA, CSO, JCMT, etc. The entries for the submm/mm observations are not complete, and many of the available measurements are very likely of unsufficient quality for our purposes.

Asteroid Number & Name	IRAS/ISO/MSX observations	Akari	Herschel PACS/SPIRE/HIFI	Submm/mm observations
(1) Ceres	y/y/n	y	PP/PS/SP/H	y
(2) Pallas	y/y/n	y	PP/PS/SP	y
(3) Juno	y/y/n	y	PP/PS/SP	y
(4) Vesta	y/y/n	y	PP/PS/SP	y
(6) Hebe	y/y/n	y	PP/PS/SP	y
(7) Iris	y/n/n	y	SP	y
(8) Flora	y/n/n	y	PP/SP	y
(9) Metis	n/y/y	y	---	y
(10) Hygiea	y/y/n	y	PP/PS/SP	y
(12) Victoria	y/n/n	y	---	y
(18) Melpomene	y/n/n	y	PP/	y
(19) Fortuna	n/n/n	y	PP/SP	y
(20) Massalia	y/y/n	y	PP/SP	y
(21) Lutetia	y/n/n	y	PP/PS/SP	y
(23) Thalia	y/n/y	y	---	n
(24) Themis	n/n/n	y	H	n
(29) Amphitrite	y/n/n	y	PP/SP	y
(37) Fides	y/n/n	y	SP	n
(40) Harmonia	y/n/n	y	SP	n
(47) Aglaja	y/n/n	y	PP/SP	n
(52) Europa	y/y/n	y	PP/PS/SP	y
(54) Alexandra	y/y/n	y	PP/ SP	n
(65) Cybele	y/y/n	y	PP/SP/H	y
(88) Thisbe	y/n/n	y	PP/PS/SP	n
(93) Minerva	y/n/y	y	PP/SP	n
(173) Ino	y/n/n	y	SP	n
(360) Carlova	y/n/n	y	PP/	n
(372) Palma	y/n/n	y	SP	n
(423) Diotima	y/n/n	y	PP/	n
(471) Papagena	y/n/n	y	---	n
(511) Davida	y/y/n	y	PP/SP	n
(532) Herculina	y/y/n	y	---	y
(704) Interamnia	y/n/n	y	PP/SP	n

VI. Current potential targets for high-quality calibrators

Based on the availability of measurements, quality of shape and spin-vector solutions, calibration purposes, quality requirements and experience, we established a list of selection criteria and tried to group the asteroids into three different categories. With the availability of new observations and possible problems in the light-curve inversion techniques, the radiometric techniques, or in case of conflicting solutions, our selection criteria might change with time, and individual objects might end up in a different category.

1. Selection criteria
   - High-quality shape solutions
   - Unique and precise spin vector information
   - Reliable size information (AO, occultations, interplanetary missions, ...)
   - Albedo information
   - Thermal properties
   - Availability of sufficient thermal data (including PACS/SPIRE measurements) for testing & validation
   - Absence of dramatic light curve features/changes
   - Avoidance of multiple objects
2. Category I objects (all have also multiple Herschel, Akari submm/mm data!)
   - (1) Ceres: Dawn model solution, multiple thermal/submm/mm data
   - (4) Vesta: Dawn model solution, multiple thermal/submm/mm data
   - (21) Lutetia: Rosetta/KOALA model solution, multiple thermal data
3. Category II objects
   - Very high-quality shape and spin-vector solutions from light curve inversion techniques
   - Multiple Herschel & Akari measurements
   - Current candidates: 3 Juno, 6 Hebe, 8 Flora, 10 Hygiea, 19 Fortuna, 29 Amphitrite, 52 Europa, 88 Thisbe, 93 Minerva, 511 Davida
4. Category III objects
   - High-quality shape and spin-vector solutions from light curve inversion techniques
   - Individual Herschel & Akari measurements
   - Objects: rest of targets with PACS and/or SPIRE observations

VII. Calibration targets which need new light curves

From our recent investigations it became clear that several objects require new light curve measurements: 10 Hygiea (long-period, incomplete light curve coverage in some apparitions), 20 Massalia (last data from 2012, model from 2002, poor fit to light curve), 37 Fides (limited data set), 47 Aglaja (long-period, low amplitude, limited data set, no light curve inversion model), 65 Cybele (low amplitude, no light curve inversion model), 93 Minerva (low amplitude, limited data set), 173 Ino (low amplitude, no good light curve inversion model), 360 Carlova (limited data set, preliminary light curve inversion model, new model by Wang et al. 2015), 372 Palma (limited data set). Source: "SBNAF Main Belt and Trojan targets needing lightcurves" (A. Marciniak, April 2016). These targets are already included in our planning for new observations (WP5).

VIII. Open points

In preparation for the upcoming deliverables and the establishment of new tools and techniques, a few open points appeared already at a very early stage. Most of the listed topics are crucial for the radiometric techniques in the context of WP4:

- Reliable source for H-G solutions (and errors)? Current references: Lagerkvist & Magnusson 1990; Lagerkvist et al. 1992; Piironen et al. 1997; Müller & Lagerros 1998, 2002; Erikson 2000, APC5, others?
- Default or specific (Vesta-like) thermal properties? (Müller & Lagerros 1998, 2002; Müller et al. 1999)
- Sufficient coverage in thermal data (wavelengths, phase angle, quality)?
- Applicability to restricted wavelength range, sky availability, brightness range, apparent size, restrictions in short-term variability, etc.
- Collection of requirements from different observatories, projects, instruments, calibration teams (collaboration with calibration experts)
- High-quality light curve observations to establish/test the zero points in time and rotational phase for meaningful mid- to long-term predictions

IX. Goals of WP4

- Establish and test of model solutions against recent light curve measurements and against Herschel PACS & SPIRE measurements (connection space-ground calibration)
- Move as many asteroids as possible to model version 2 (including good-quality shape and unique spin properties, good-quality size and albedo information, well-constrained thermal properties) --> category I+II+III
- Evaluate possibilities to go to model version 3 for selected targets for fulfilling highest accuracy requirements for specific calibration applications --> category I and selected category II targets
- React to specific requirements and needs for various ground, airborne, and space projects
- Document all on-going activities and publish new and improved calibrators for far-IR/submm/mm ground, air-borne and space projects
- Provide ready-to-use calibration products to relevant observatories.

X. Important reference articles in this context

- Müller & Lagerros (1998), A&A, 338, 340: Asteroids as far-infrared photometric standards for ISOPHOT
- Müller & Lagerros (2002), A&A, 381, 324: Asteroids as calibration standards in the thermal infrared for space observatories
- Müller et al. (2005), ESA SP-577, 471: The Asteroid Preparatory Programme for HERSCHEL, ASTRO-F & ALMA
- Müller et al. (2014), Exp. Astron, 37, 253: Herschel celestial calibration sources. Four large main-belt asteroids as prime flux calibrators for the far-IR/sub-mm range