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	**WP4 Asteroid-related calibration**
Del.No	**D4.5**
Title	**Final asteroid models**
Lead Beneficiary	MPG
Nature	Report
Dissemination Level	Public
Est. Del. Date	31 Mar 2019
Version	1.0
Date	02 May 2019
Lead Author	T. Müller, MPE, tmueller@mpe.mpg.de
Co-Authors	V. Alí-Lagoa, A. Marciniak

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 D4.5
Final model solutions (version 2) for primary and secondary calibration asteroids available.

Description of deliverable

I. Introduction

The context for using asteroids as far-IR/submm/mm calibration purposes was presented and discussed in D4.1. As a first step (in D4.2) we provided preliminary model predictions (model version 0) for 20 asteroids for the time period 2016 to 2020. These predictions are only meant for planning purposes: to find a good-quality calibrator in the required flux regime for specific calibration applications. These predictions are used worldwide by all major far-IR/submm/mm projects (ground-based, airborne, and space observatories). In D4.3 we focused on high-quality model prediction of asteroid fluxes (at far-IR/submm/mm wavelengths) for direct calibration purposes. These flux predictions (called asteroid model version 2) are based on sophisticated models for selected asteroids, and including daily and seasonal variations due to rotation, changing Sun-observer-target distances, phase and aspect angles. Predictions were done for four asteroids (1 Ceres, 2 Pallas, 4 Vesta, and 21 Lutetia), for the time period 2014 to 2020 (also to be used for past ALMA/SOFIA/IRAM/etc. calibration observations). In addition, the deliverable D4.3 included also specific TPM calculations (FITS files with model SEDs) for all Herschel PACS and SPIRE photometric observations of the asteroids 1 Ceres, 2 Pallas, 4 Vesta, and 21 Lutetia (calibration and science observations; one model FITS file for each OBSID) for direct upload to the Herschel Science Archive. These Herschel model requests include the detailed model and observing parameters, as well as the observation-specific parameters (OD, OBSID, instrument and observing mode) as FITS header keywords.

In D4.6 we discussed the selection process for additional secondary calibrators, trying to fulfil the calibration requirements of different projects. We also tried to establish criteria for the final selection. In D4.4, we applied the selection recipes to more than 10 asteroids, resulting in 7 good-quality secondary calibrators: (3) Juno, (6) Hebe, (7) Iris, (8) Flora, (9) Metis, (24) Themis, (65) Cybele. These objects complemented our primary calibrators (1) Ceres, (2) Pallas, (4) Vesta, and (21) Lutetia (see D4.3). Several of our earlier candidates (see D4.6) had to be rejected at this stage due to the lack of high-quality thermal data, poor or ambiguous spin/shape solutions, or problems in finding acceptable and unique model solutions (spin, shape, size, albedo, thermal inertia, surface roughness, emissivity).

Predictions for more asteroids (also model versions 1 and higher) for direct calibration applications are now part of deliverable D4.5 (which completes WP4). It connects the conducted work (and deliverables) in WP2, WP3, WP4, WP5, and WP6 of the SBNAF project.

II. Final SBNAF asteroid calibrator models

The following asteroids fulfilled our requirements:

- large main-belt asteroids
- high-quality spin-shape solutions, not too extreme shapes, no (large) satellites, high accuracy of rotational properties which allow a precise phasing of the spin-shape solutions at least in the time period 2000-2020, see Deliverables D3.3, 6.8
- availability of sufficient thermal infrared observations from different missions/projects, covering a substantial wavelength range from mid-IR to far-IR, with data before and after opposition (IRAS, MSX, AKARI, WISE, Herschel-PACS)
- radiometric size, albedo, thermal solutions with reduced χ^2 close to 1.0 or lower (fitting the available data reasonably well)
- additional size information from direct measurements like occultations, AO imaging or interplanetary missions

List of objects, established as primary (bold face) and secondary calibrators in previous deliverables (which were all tested against various submm/mm observations):

1 Ceres	**2014-2020, v2**	**D4.3**
2 Pallas	**2014-2020, v2**	**D4.3**
4 Vesta	**2014-2020, v2**	**D4.3**
21 Lutetia	**2014-2020, v2**	**D4.3**
3 Juno	2018-2020	D4.4
6 Hebe	2018-2020	D4.4
7 Iris	2018-2020	D4.4
8 Flora	2018-2020	D4.4
9 Metis	2018-2020	D4.4
24 Themis	2018-2020	D4.4
65 Cybele	2018-2020	D4.4

List of new secondary calibrators established in the context of D4.5 (tested against mid-/far-IR observations, but usually lacking submm/mm observations to test the model predictions):

Object	**No obs**	**Model**	**Red. χ^2**		
12 Victoria	**30**	**ADAM, V+17**	**<1.0**	**2018-2020**	**D4.5**
18 Melpomene	**58**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
19 Fortuna	**22**	**ADAM, H+17b**	**1.02**	**2018-2020**	**D4.5**
20 Massalia	**71**	**SAGE1**	**<1.0**	**2018-2020**	**D4.5**
23 Thalia	**31**	**ADAM2, V+17**	**<1.0**	**2018-2020**	**D4.5**
29 Amphitrite	**45**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
37 Fides	**37**	**SAGE1**	**<1.0**	**2018-2020**	**D4.5**
40 Harmonia	**40**	**ADAM, V+17**	**<1.0**	**2018-2020**	**D4.5**
52 Europa	**101**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**

54 Alexandra	**49**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
88 Thisbe	**59**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
93 Minerva	**30**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
360 Carlova	**56**	**SAGE2**	**1.01**	**2018-2020**	**D4.5**
372 Palma	**45**	**LI, D+11, H+11**	**<1.0**	**2018-2020**	**D4.5**
423 Diotima	**30**	**ADAM, H+18**	**<1.0**	**2018-2020**	**D4.5**
471 Papagena	**22**	**ADAM, H+17b**	**1.00**	**2018-2020**	**D4.5**
511 Davida	**47**	**ADAM, V+17**	**<1.0**	**2018-2020**	**D4.5**
532 Herculina	**25**	**ADAM, H+17b**	**<1.0**	**2018-2020**	**D4.5**
704 Interamnia	**119**	**SAGE1**	**1.08**	**2018-2020**	**D4.5**

The observations are from IRAS, MSX, WISE, AKARI, and Herschel-PACS. They were all taken from our IR database of thermal asteroid measurements (D2.6, see at https://ird.konkoly.hu. The shape models were taken from the ISAM service (http://isam.astro.amu.edu.pl) or from the DAMIT database (https://astro.troja.mff.cuni.cz/projects/asteroids3D), the reference are: H+11: Hanuš et al. 2011, A&A 530, A134; Durech et al. 2011, Icarus 214, 652; H+17b: Hanuš et al. 2017b, A&A 601, A114; V+17: Viikinkoski et al. 2017, A&A 607, A117; Hanuš et al. 2018, Icarus 299, 84. The reduced χ^2 values are all close to 1.0 (or below) and indicate that the given spin-shape solutions fit all available thermal data within the given error bars. We consider this aspect as a requirement for accepting a given asteroid as potential calibrator. However, some of the asteroids (and the corresponding radiometric solutions) still show some residuals or a lack of coverage in the wavelength – phase angle – aspect angle – rotational phase – etc. parameter space. Here are some relevant notes for our targets (in addition to the information given in D3.3, D3.5, D3.6, D6.5, and D6.8):

- (12) Victoria: small number of thermal measurements, before/after opposition not well balanced, AKARI 9-micron data are slightly off; WISE W4 well fitted on absolute level and also no residuals in rotational phase. No Herschel data.
- (18) Melpomene: The radiometric solution explains all thermal measurements (IRAS, AKARI, WISE, and Herschel-PACS) but requires a 7% scaling of the original ADAM shape, which is higher than the average scaling of ~3% required for other ADAM shapes. The data before/after opposition are not well balanced; possibly shape residuals in the rotational phase analysis; large eccentricity from 1.8-2.8 AU which might require changing thermal properties in the radiometric predictions.
- (19) Fortuna: Low orbit inclination, low pole obliquity; high eccentricity from 2.0 to 2.85 AU could be problematic; possibly some residuals in the rotational phase picture (shape problems?).
- (20) Massalia: There are residual "waves" in the rotational phase plot; large range in heliocentric distance from 2.0 to 2.8 AU.
- (23) Thalia: only IRAS, MSX and AKARI data.
- (29) Amphitrite: IRAS, AKARI, WISE, PACS data. Good fit, no obvious problems.

- (37) Fides: large range in heliocentric distances (2.2 to 3.1 AU), possibly with changing thermal parameters. Mainly IRAS and AKARI data, no PACS data and only one set of WISE data.
- (40) Harmonia: IRAS, AKARI, WISE data. Reasonable fit.
- (52) Europa: Good fit to the available thermal data (IRAS, AKARI, WISE, PACS).
- (54) Alexandra: IRAS, AKARI, WISE, PACS data. Excellent fit, but only northern and equatorial sub-observer points sampled. Not well balanced before/after opposition, residuals in rotational phase plot (seen in WISE 22-micron data), heliocentric range from 2.2 to 3.0 AU.
- (88) Thisbe: Very good fit, but it has a high pole obliquity and the TPM did not sample pole-on views, so they'd have a higher uncertainty.
- (93) Minerva: IRAS, MSX, AKARI, PACS data. Some issues with fitting all data simultaneously.
- (360) Carlova: new SAGE2 solution based on many new, good-quality lightcurves, some issues with fitting all data simultaneously, the WISE W4 data still show some structure in the rotational phase plot, large range of heliocentric distances from 2.6 to 3.5 AU.
- (372) Palma: IRAS, AKARI, WISE data. Reasonable fit.
- (423) Diotima: IRAS, AKARI, WISE, and PACS data. Good fit, but sampled northern hemisphere, mostly.
- (471) Papagena: Good fit, but the data set is small (IRAS, AKARI only).
- (511) Davida: Quite irregular and possible surface variability. Data mostly sampled the southern hemisphere.
- (532) Herculina: Only northern-pole and "tropical" views (IRAS, AKARI, WISE).
- (704) Interamnia: Lots of data (IRAS, AKARI, WISE, PACS), Fit is acceptable, but there are clear outliers (in the rotational phase plot). Large range of heliocentric distance from 2.6 to 3.5 AU. It seems, there are some shape issues and/or strong albedo variations on the surface.

We also tested a few other objects in the context of D4.5, but we rejected them for calibration purposes for the following reasons:

- Showing evidence for possible strong albedo variations (10 Hygiea)
- Poor spin-shape solutions (47 Aglaja, 173 Ino)

Therefore, at the end of the SBNAF project, we have now **4 primary calibrators** (Ceres, Pallas, Vesta, Lutetia) which have excellent spin-shape solutions, and sufficient submm/mm data for testing the critical calibration regime. In addition, we have established **7 secondary calibrators (in D4.4)** where spin and shape properties are known (although other properties are less accurate), and tested against submm/mm observations. However, very few high-quality test measurements at long wavelengths were available. Here, in we added another **19 secondary calibrators (in D4.5)** with good-quality spin-shape solutions, direct size information, and sufficient mid-/far-IR observations (IRAS, MSX, AKARI, WISE, Herschel-PACS) to do a robust model validation. In total, we have now 4 primary calibrators and 26 (7 in D4.4 and 19 in 4.5) secondary calibrators.

All these spin-shape solutions are available from the public ISAM service (only Fides and Carlova are currently available only on the internal ISAM). Many of the solutions were established during the SBNAF project (WP3), including also many observations obtained during the last years (WP5). The thermal data which were used for the D4.5 testing of the secondary calibrators, are available from the SBNAF database of infrared observations of asteroids (WP2). The radiometric analysis, the cross-check against AO imaging and occultation information was done as part of WP6.

Based on our tested and verified asteroid thermophysical model solutions (shape, spin, size, albedo, thermal properties, H-G values), we made flux predictions at multiple far-IR, submm, mm wavelengths for calibration purposes. These predictions have a time resolution of 15 min (to account for the rotational flux changes). The typical absolute flux accuracies are around 5-10%, depending on the object, wavelengths, rotational phase, aspect angles, and time of the observation. There are clearly gaps in our testing procedures due to the limited thermal IR data available for each object which could mean that for specific times and wavelength (or frequencies) the accuracy might be outside our 10% boundary. A few of the targets (704 is the most problematic one in that respect) have residuals in fitting the observed rotational variations in the thermal IR (coming either from WISE W4 data and/or from Herschel-PACS). Here, we found differences between model predictions and measured fluxes which are larger than 10% (at some rotational phases, or for specific aspect angles).

III. Products

The model predictions for all the targets for the time period 2018-2020, with a 15-min time resolution, can be found at:
http://www.mpe.mpg.de/~tmueller/sbnaf/results/bProducts.html.
The predictions are done at 10 reference frequencies/wavelengths between 30 and 1000 GHz (10,000 to 300 micron). Figures 1, 2, and 3 show the absolute fluxes of all 25 asteroids (D4.4 and D4.5) over the entire 3-year period. The overall flux change is mainly related to a change in observing geometry (asteroid's helio- and geo-centric distance, and phase angle). Figures 4, 5, and 6 show the same data, but just for the first day (Jan 1, 2018). Here, the variations are related to the object's shape and spin properties.

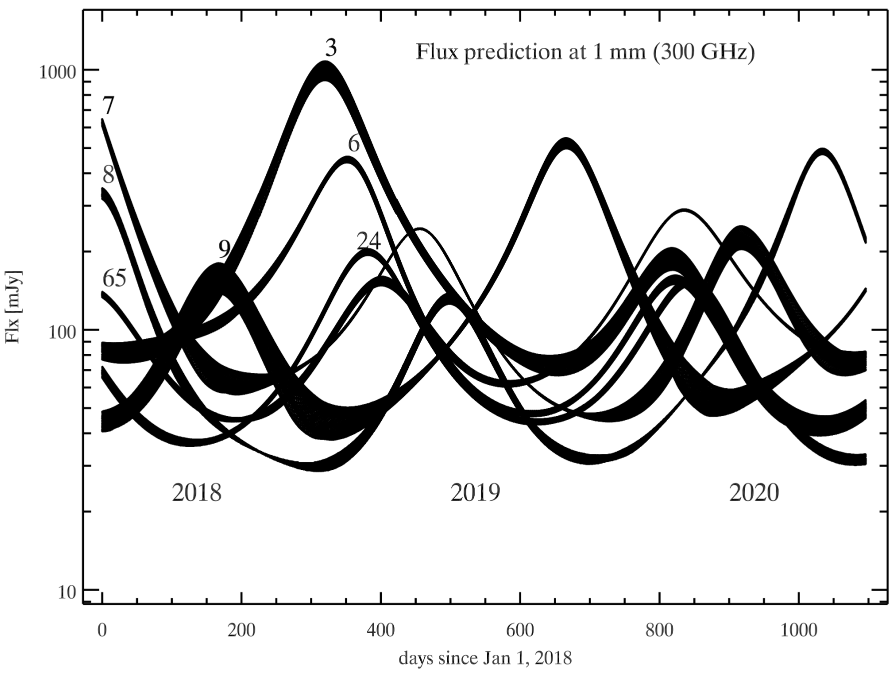

Figure 1: *The 1-mm (300 GHz) flux predictions for our list of secondary asteroid calibrators presented in D4.4. The overall change in flux is related to the changing observing geometry. The line width shows the amplitude of the short-term variations due to the object's shape and rotation. Targets are: 3, 6, 7, 8, 9, 24, and 65.*

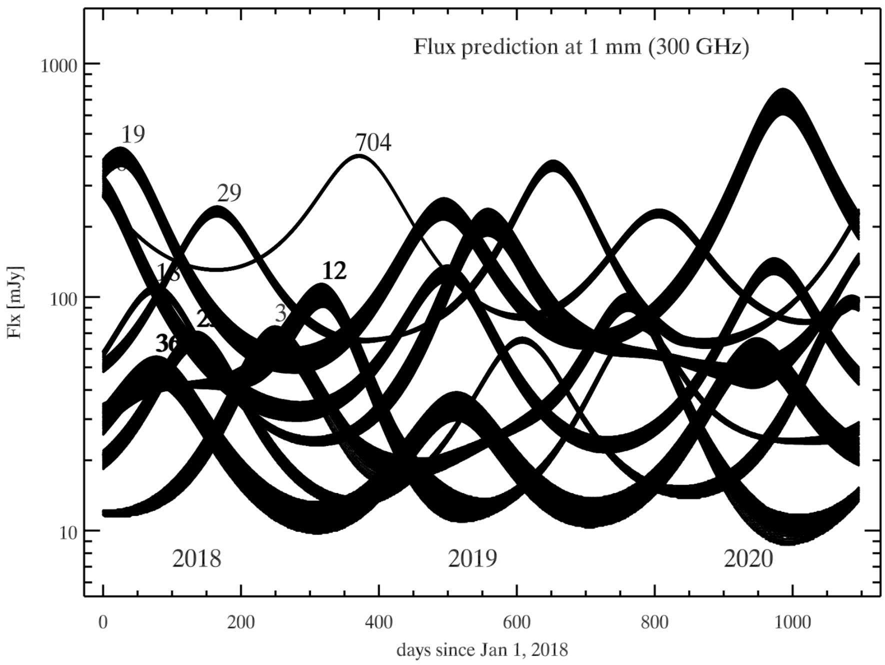

Figure 2: *The 1-mm (300 GHz) flux predictions for our list of secondary asteroid calibrators presented in D4.5 (first part). The overall change in flux is related to the changing observing geometry. The line width shows the amplitude of the short-term variations due to the object's shape and rotation. Targets are: 12, 18, 19, 20, 23, 29, 37, 360, and 704.*

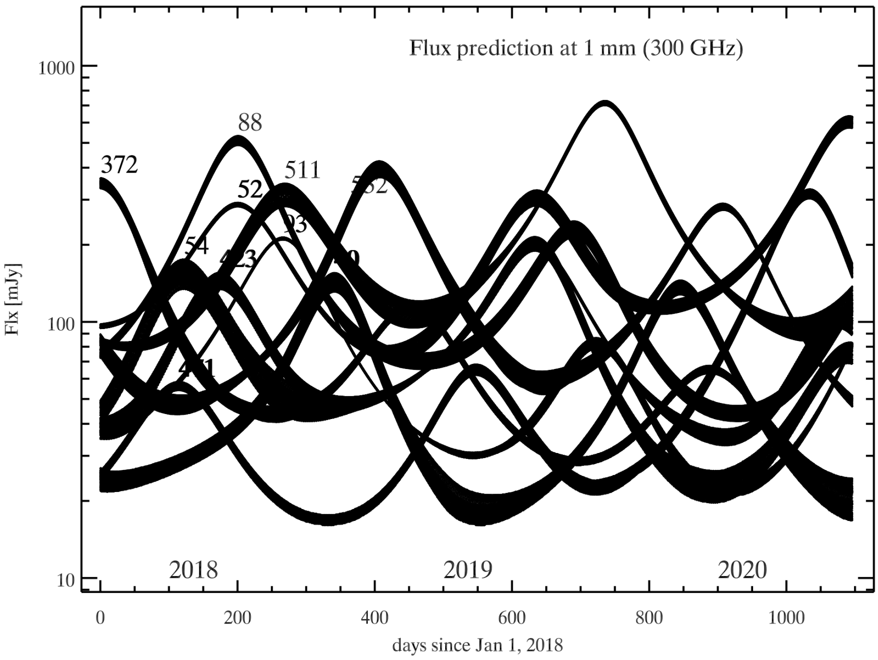

Figure 3: *The 1-mm (300 GHz) flux predictions for our list of secondary asteroid calibrators presented in D4.5 (second part). The overall change in flux is related to the changing observing geometry. The line width shows the amplitude of the short-term variations due to the object's shape and rotation. Targets are: 40, 52, 54, 88, 93, 372, 423, 471, 511, and 532.*

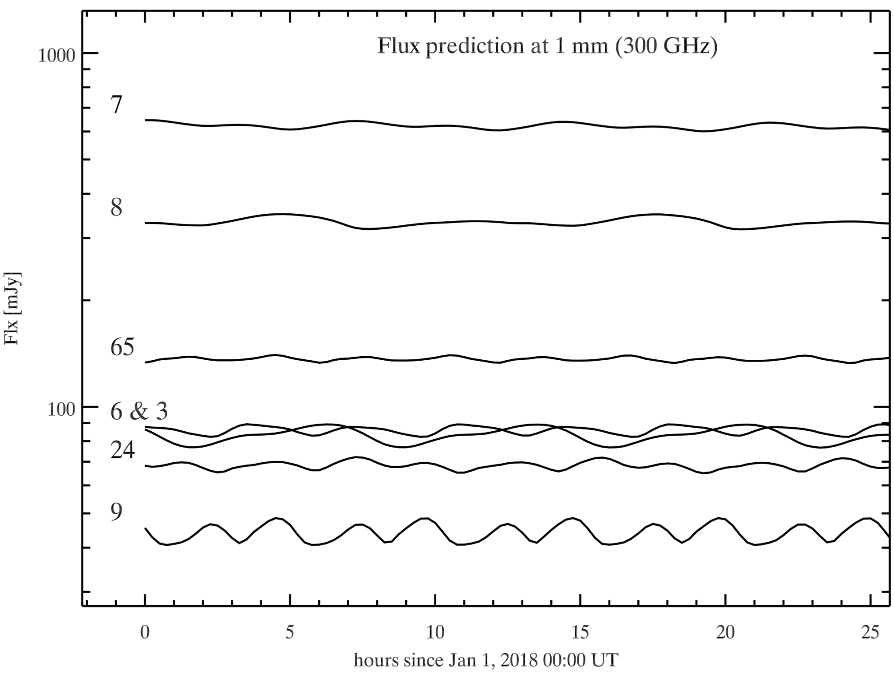

Figure 4: *The 1-mm (300 GHz) flux predictions are shown for Jan 1, 2018. The absolute flux scale is accurate on a 5-10% level. The variations shown for each object are related to the object's shape and spin properties. Calculations are done for the ALMA site (observatory code: -7). Secondary calibrators are from D4.4. Targets are: 3, 6, 7, 8, 9, 24, and 65.*

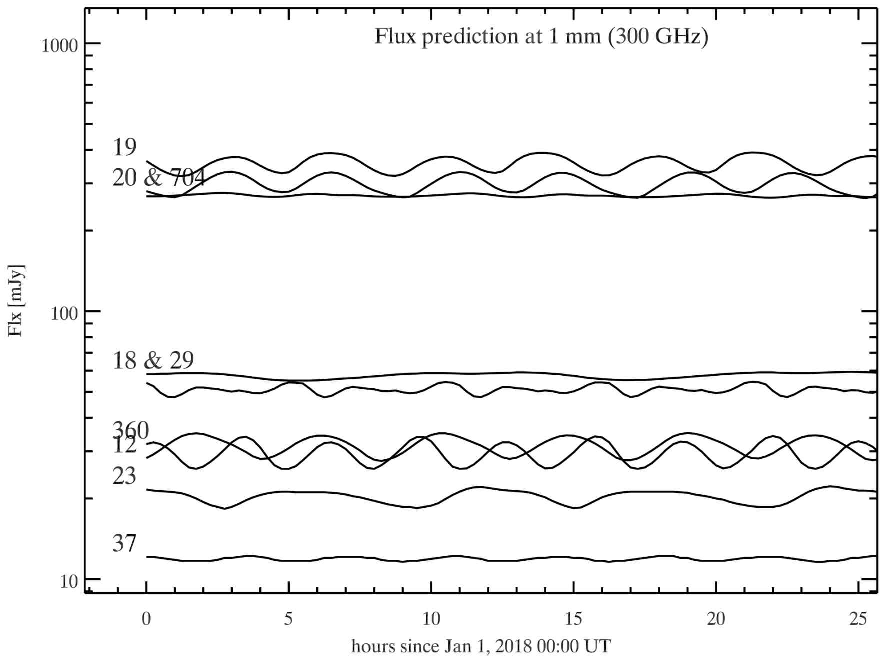

Figure 5: *The 1-mm (300 GHz) flux predictions are shown for Jan 1, 2018. The absolute flux scale is accurate on a 5-10% level. The variations shown for each object are related to the object's shape and spin properties. Calculations are done for the ALMA site (observatory code: -7). Secondary calibrators are from D4.5 (first part). Targets are: 12, 18, 19, 20, 23, 29, 37, 360, and 704.*

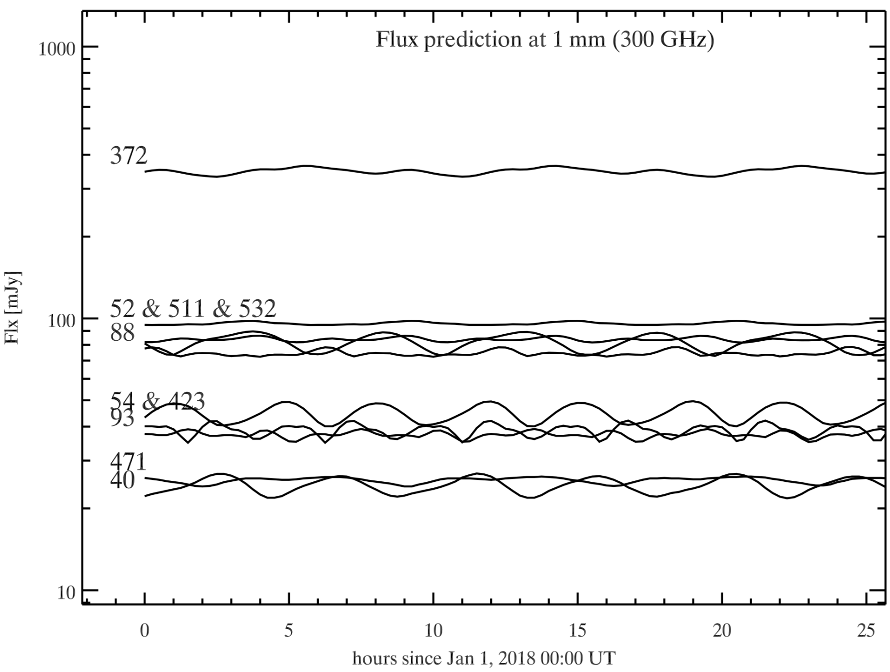

Figure 6: *The 1-mm (300 GHz) flux predictions are shown for Jan 1, 2018. The absolute flux scale is accurate on a 5-10% level. The variations shown for each object are related to the object's shape and spin properties. Calculations are done for the ALMA site (observatory code: -7). Secondary calibrators are from D4.5 (second part). Targets are: 40, 52, 54, 88, 93, 372, 423, 471, 511, and 532.*

The current set of secondary asteroids covers (at 1-mm wavelengths) a flux range from a few 10 mJy up to about 1 Jy. At shorter wavelengths (higher frequencies) the objects are brighter, at longer wavelengths (lower frequencies) the objects are fainter, following roughly a Rayleigh-Jeans spectral energy distribution.

The products generated for D4.3 are available on the internal and public SBNAF web pages:

- D4.3 Calibration asteroid model predictions (30 Sep 2016, done)
  - High-quality & high time resolution TPM predictions at 10 reference frequencies (model v2) for Ceres, Pallas, Vesta, Lutetia for 2014-2020 (gzipped tar file with 28 txt-files: one per object per year)
  - Model predictions (model v1 & v2) for all 28 Herschel-PACS/SPIRE/HIFI calibration asteroids at observation mid-time for HSA upload (gzipped tar file with 1433 FITS files, corresponding to 1433 OBSIDs or 359.13 h total Herschel observing time)
  - Release note for HSA upload of asteroid model predictions (pdf)

The products generated for D4.4 are available on the internal and public SBNAF web pages:

- D4.4 Secondary asteroid models (31 Mar 2018)
  These secondary asteroid model predictions (2018-2020, 15-min time resolution) are based on new spin-shape solutions (derived from combined lightcurve, occultation, AO observations), combined with radiometrically derived size, albedo, and thermal properties. The models have been tested against available and well-calibrated submm/mm data from Herschel-SPIRE, CSO, ALMA, APEX. Estimated absolute model accuracy in the submm/mm range: +/- 5-10%
  - (3) Juno: 2018, 2019, 2020 (txt files)
  - (6) Hebe: 2018, 2019, 2020 (txt files)
  - (7) Iris: 2018, 2019, 2020 (txt files)
  - (8) Flora: 2018, 2019, 2020 (txt files)
  - (9) Metis: 2018, 2019, 2020 (txt files)
  - (24) Themis: 2018, 2019, 2020 (txt files)
  - (65) Cybele: 2018, 2019, 2020 (txt files)

  The detailed model solutions are available on request.

The products generated for D4.5 are available on the internal and public SBNAF web pages:

- D4.5 Final asteroid models (31 Mar 2019)
  These secondary asteroid model predictions (2018-2020, 15-min time resolution) are based on new spin-shape solutions (derived from combined lightcurve, occultation, AO observations), combined with radiometrically derived size, albedo, and thermal properties. The models have been tested against available and well-calibrated mid-/far-IR data from IRAS, MSX, AKARI, WISE, and Herschel-PACS. Estimated absolute model accuracy are around 10%, but maybe up to 20% in the submm/mm where test data are missing, or in cases where the shape models are suffering from albedo variations or a lack of good-quality lightcurves or poor coverages in aspect angles.
  - (12) Victoria: 2018, 2019, 2020 (txt files)
  - (18) Melpomene: 2018, 2019, 2020 (txt files)
  - (19) Fortuna: 2018, 2019, 2020 (txt files)
  - (20) Massalia: 2018, 2019, 2020 (txt files)
  - (23) Thalia: 2018, 2019, 2020 (txt files)
  - (29) Amphitrite: 2018, 2019, 2020 (txt files)
  - (37) Fides: 2018, 2019, 2020 (txt files)
  - (40) Harmonia: 2018, 2019, 2020 (txt files)
  - (52) Europa: 2018, 2019, 2020 (txt files)
  - (54) Alexandra: 2018, 2019, 2020 (txt files)
  - (88) Thisbe: 2018, 2019, 2020 (txt files)
  - (93) Minerva: 2018, 2019, 2020 (txt files)
  - (360) Carlova: 2018, 2019, 2020 (txt files)
  - (372) Palma: 2018, 2019, 2020 (txt files)
  - (423) Diotima: 2018, 2019, 2020 (txt files)
  - (471) Papagena: 2018, 2019, 2020 (txt files)
  - (511) Davida: 2018, 2019, 2020 (txt files)
  - (532) Herculina: 2018, 2019, 2020 (txt files)
  - (704) Interamnia: 2018, 2019, 2020 (txt files)

  The detailed model solutions are available on request.