Delivery Note

Asteroid thermophysical model predictions for HSA upload

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Related Workpackage: WP4 Asteroid-related calibration
Related Deliverable: D4.3 Calibration asteroid model predictions

Description of delivery

I. Introduction

The context for using asteroids as far-IR/submm/mm calibration purposes was presented and discussed in SBNAF D4.1 and D4.2 (available at http://www.mpe.mpg.de/~tmueller/sbnaf/results/WP4_AstCal.html). Here, we focus on Herschel-specific thermo-physical model prediction of asteroid fluxes (at far-IR/submm/mm wavelengths) for **direct calibration purposes**.

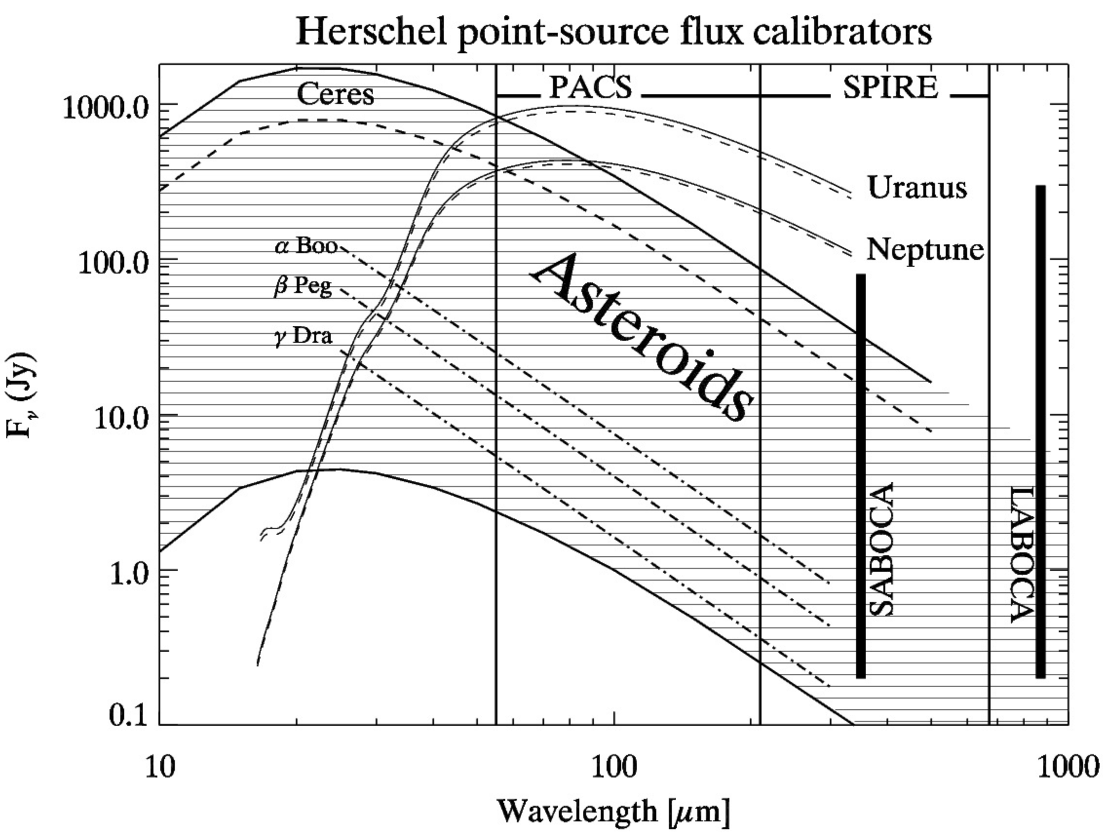


Fig 1: *The spectral energy distributions of the brightest calibration stars (used at mid-IR wavelengths), Uranus/Neptune (used often at submm/mm wavelengths) and the shaded area which is covered by a few large and well-known asteroids. The Herschel-PACS and SPIRE ranges are shown, as well as APEX SABOCA/LABOCA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

II. Herschel observations

Herschel (2009-2013) observed 28 different asteroids for calibration purposes (see Table in Section "V. Information about key thermal IR observations" and table below). Here is a short summary of the number of asteroid observations in the relevant observing modes and the corresponding observing times (as extracted from "duration" in the science and calibration observation log files):

1) Asteroid total observing time in each mode (in hours)

PacsPhoto	59.42 h
PacsSpec	124.67 h
SpirePhoto	94.01 h
SpireSpec	63.56 h
HifiPoint	17.48 h
Total	**359.14h**

2) prime asteroid calibrators (model v2): Ceres, Pallas, Vesta, Lutetia

PacsPhoto	236 OBSIDs
PacsSpec	164 OBSIDs
SpirePhoto	202 OBSIDs
SpireSpec	76 OBSIDs
HifiPoint	6 OBSIDs
Total	**684 OBSIDs**

3) secondary asteroid calibrators (model v1): Aglaja, Alexandra, Amphitrite, Carlova, Cybele, Davida, Diotima, Europa, Fides, Flora, Fortuna, Harmonia, Hebe, Hygiea, Ino, Interamnia, Iris, Juno, Massalia, Melpomene, Minerva, Palma, Themis, Thisbe

PacsPhoto	294 OBSIDs
PacsSpec	107 OBSIDs
SpirePhoto	228 OBSIDs
SpireSpec	118 OBSIDs
HifiPoint	2 OBSIDs
Total	**749 OBSIDs**

4) all asteroids and the corresponding observing modes: only Ceres is available in all 5 modes (see also Müller et al. 2014, ExA 37)

Asteroid Number & Name	PacsPhoto	PacsSpec	SpirePhoto	SpireSpec	HifiPoint
(1) Ceres	Y	Y	Y	Y	Y
(2) Pallas	Y	Y	Y	Y	
(3) Juno	Y	Y	Y	Y	
(4) Vesta	Y	Y	Y	Y	
(6) Hebe	Y	Y	Y	Y	
(7) Iris			Y	Y	
(8) Flora	Y		Y	Y	
(10) Hygiea	Y	Y	Y	Y	
(18) Melpomene	Y				
(19) Fortuna	Y	Y	Y	Y	
(20) Massalia	Y		Y		

(21) Lutetia	Y	Y	Y	Y	
(24) Themis					Y
(29) Amphitrite	Y		Y		
(37) Fides			Y		
(40) Harmonia			Y		
(47) Aglaja	Y		Y		
(52) Europa	Y	Y	Y	Y	
(54) Alexandra	Y		Y		
(65) Cybele	Y		Y	Y	Y
(88) Thisbe	Y	Y	Y	Y	
(93) Minerva	Y		Y		
(173) Ino			Y		
(360) Carlova	Y				
(372) Palma			Y		
(423) Diotima	Y				
(511) Davida	Y		Y		
(704) Interamnia	Y		Y		

III. Model settings

The calculations were done via a thermophysical model code (Lagerros 1996, 1997, 1998, Müller & Lagerros 1998, 2002). The model input parameters are listed in the FITS header (see example in the appendix). The primary asteroid models (post-Herschel v2 models) and comparisons with the observations are presented and discussed in Müller et al. (2014), the secondary asteroid models (model v1) are still pre-Herschel models. These models will be updated as part of the EU-funded project SBNAF during the period 2016-2019. The corresponding SBNAF deliverables are:

- D4.6 Selection of secondary asteroid calibrators (31 Mar 2017)
- D4.4 Secondary asteroid models (31 Mar 2018)
- D4.5 Final asteroid models (31 Mar 2019)

All models include dedicated shape and spin solutions for each asteroid to account for rotational flux variations. Each predictions is made for the Herschel observation mid-time, observing and illumination geometry as seen from Herschel, and in the Herschel time reference system. The models are spectral energy distributions with the following wavelength ranges and sampling densities:

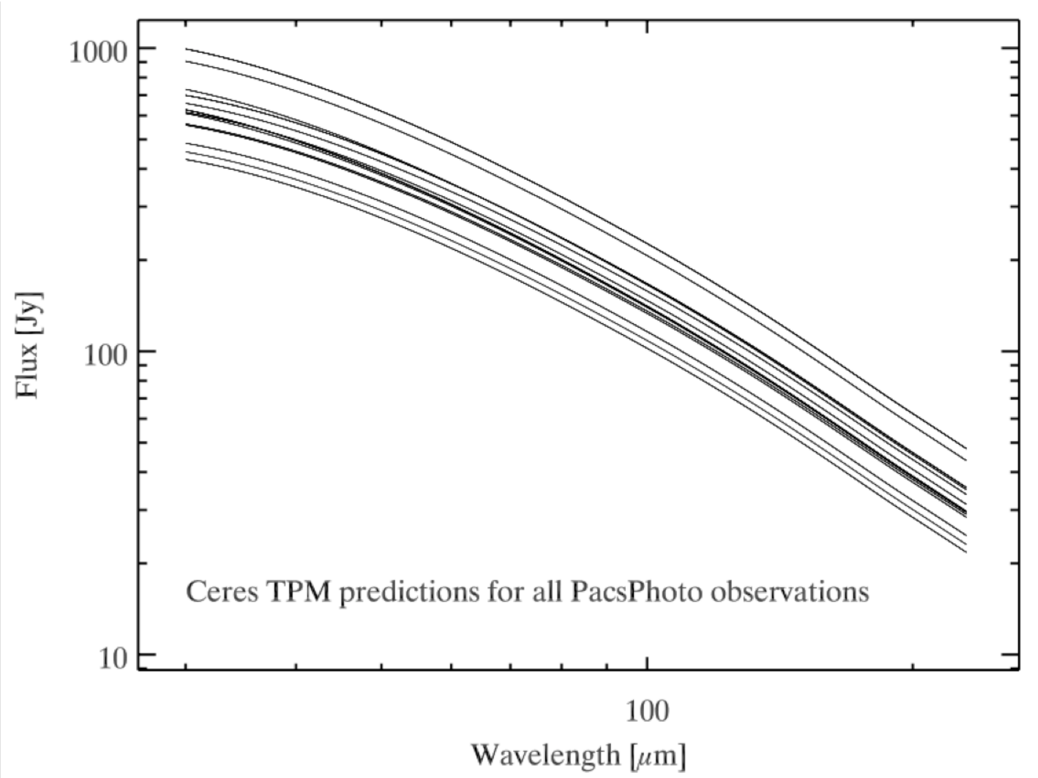
Mode	Start wavelength [μm]	End wavelength [μm]	Sampling step size [μm]
PacsPhoto	30	230	1.0
PacsSpec	30	230	1.0
SpirePhoto	150	750	1.0
SpireSpec	150	750	1.0
HifiPoint	150	750	1.0

The FITS file naming convention is the following:
"JTPM_0103_1342182817_Fortuna_v1.fits"

- JTPM: Johan's Thermo-Physical Model
- 0130: Herschel OD
- 1342182817: Herschel OBSID
- Fortuna: asteroid name
- V1: model version number (here: either v1 or v2)

IV. Prime asteroid calibrators

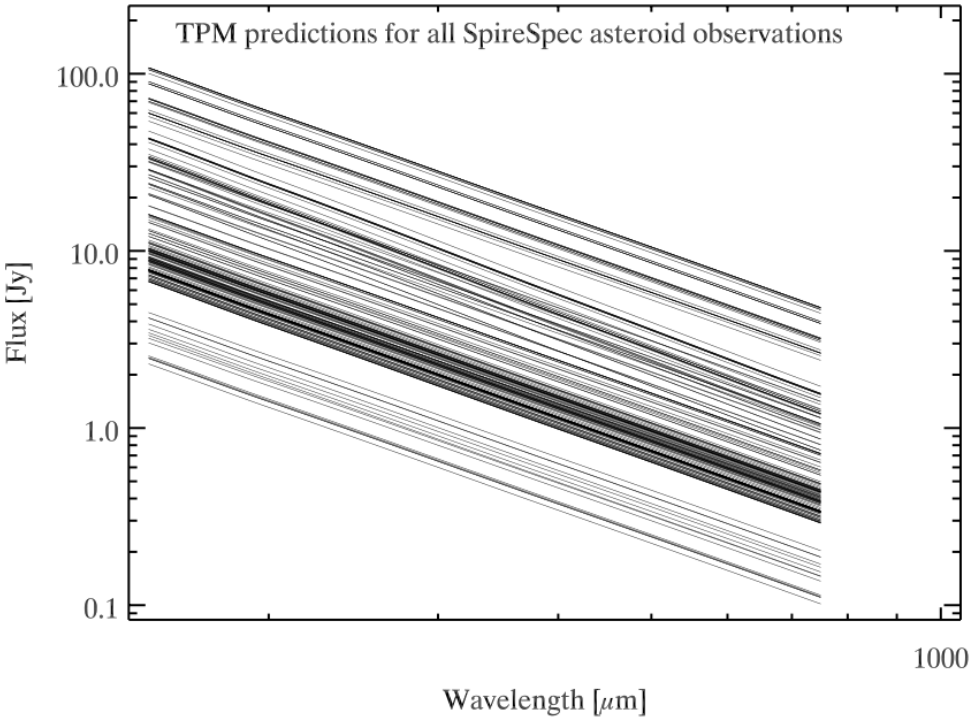
Müller et al. (2014) presented newly established models for the four large and well characterized main-belt asteroids (1) Ceres, (2) Pallas, (4) Vesta, and (21) Lutetia which can be considered as new prime flux calibrators. The relevant object-specific properties (size, shape, spin-properties, albedo, thermal properties) are well established. The seasonal (distance to Sun, distance to observer, phase angle, aspect angle) and daily variations (rotation) are included in a new thermophysical model setup for these targets. **The thermophysical model predictions (model v2) agree within 5 % with the available (and independently calibrated) Herschel measurements.** The four objects cover the flux regime from just below 1,000 Jy (Ceres at mid-IR N-/Q-band) down to fluxes below 0.1 Jy (Lutetia at the longest wavelengths). Based on the comparison with Herschel-PACS, SPIRE and HIFI measurements and pre-Herschel experience, the validity of these new prime calibrators ranges from mid-infrared to about 700 μm, connecting nicely the absolute stellar reference system in the mid-IR with the planet-based calibration at sub-mm/mm wavelengths.



Model details are given in Müller et al. 2014. Updates for these models are currently in preparation (will then be model v3). All Herschel-specific calibration models are available on the public SBNAF web pages with access for the Herschel Science Team, as well as other calibration experts worldwide.

V. Secondary asteroid calibrators

For the secondary calibrator models (v1) we used pre-Herschel settings. All parameters are listed in the FITS header keywords. **The thermophysical model predictions (model v1) are expected to agree within 5-30 % with the available thermal measurements.** Updates for these models are currently in preparation (will then be model v2). The updates will include more reliable shape and spin solutions, as well as better size and albedo solutions. All Herschel-specific calibration models are available on the public SBNAF web pages with access for the Herschel Science Team, as well as other calibration experts worldwide.



VI. Herschel Science Team contact points

In the Herschel calibration context the following contact points have been established:

- Anthony Marston, tmarston@sciops.esa.int --> HCalSG chair
- Tanya Lim, tlim@sciops.esa.int --> SPIRE contact point
- David Teyssier, dteyssier@sciops.esa.int --> new contact point for HSA upload of FITS model prediction
- Glenn Orton, Glenn.S.Orton@jpl.nasa.gov --> comparison with planet models
- Raphael Moreno, raphael.moreno@obspm.fr --> comparison with planet models
- Michael Olberg, michael.olberg@chalmers.se --> contact point for HIFI observations
- Eva Verdugo, eva.verdugo@sciops.esa.int --> HSA upload
- Pedro Garcia-Lario, pedro.garcia-lario@sciops.esa.int --> HST coordinator

VII. Important reference articles in this context

- **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**

- Lagerros (1996): A&A, 310, 1011: Thermal physics of asteroids. I. Effects of shape, heat conduction and beaming.

- Lagerros (1997): A&A, 325, 1226: Thermal physics of asteroids. III. Irregular shapes and albedo variegations.
- Lagerros (1998): A&A, 332, 1123: Thermal physics of asteroids. IV. Thermal infrared beaming
- 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. (2016), A&A 588, A109: Far-infrared photometric observations of the outer planets and satellites with Herschel-PACS
- Harris (1998), Icarus 131, 291-301: A Thermal Model for Near-Earth Asteroids
- Lebofsky et al. (1986), Icarus 68, 239-251: A refined 'standard' thermal model for asteroids based on observations of 1 Ceres and 2 Pallas
- Bowell et al. (1989 in R.P. Binzel, T. Gehrels and M.S. Matthews (eds.), Asteroids II, pp 524-556, The University of Arizona Press: Application of photometric models to asteroids
- Kiss et al. (2005), A&A 430, 343-353: Determination of confusion noise for far-infrared measurements

Appendix

Here is an example “JTPM_0103_1342182817_Fortuna_v1.fits” for the FITS header keywords:

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                 3216 / width of table in bytes
NAXIS2  =                    1 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    4 / number of fields in each row
TTYPE1  = 'WAVE    '           / label for field 1
TFORM1  = '201E    '           / data format of field: 4-byte REAL
TUNIT1  = 'micron  '           / physical unit of field
TTYPE2  = 'JY_FLUX '           / label for field 2
TFORM2  = '201E    '           / data format of field: 4-byte REAL
TUNIT2  = 'Jy      '           / physical unit of field
TTYPE3  = 'FERR    '           / label for field 3
TFORM3  = '201E    '           / data format of field: 4-byte REAL
TUNIT3  = 'Jy      '           / physical unit of field
TTYPE4  = 'EMISSIV '           / label for field   4
TFORM4  = '201E    '           / data format of field: 4-byte REAL
EXTNAME = 'jlmdata '           / name of this binary table extension
SOURCE  = 'Fortuna '           / Asteroid name
PAR_NUMB= '0019    '           / Asteroid number
```

```
ODNUMBER= '0103    '           / Operational day number
OBS_ID  = '1342182817'         / Observation identifier
INSTRUME= 'PACS    '           / Instrument attached to this product
MODE    = 'PacsSpec'           / Instrument observing mode
SED_DATE= '16278   '           / YYDAY of creation of FITS file
SED_TIME= '155535  '           / time HHMMSS of creation of FITS file
TIMEKEY = '09237080630'        / timekey YYDAYHHMMSS of the SED
PAR_SIZE=            2.063E+02 / [km] effective diameter
PAR_AXA =            1.191E+02 / [km] semi-major axis a
PAR_AXB =            9.914E+01 / [km] semi-major axis b
PAR_AXC =            9.296E+01 / [km] semi-major axis c
PAR_SHPM= 'irregular'          / shape model
PAR_LS  =              9.8E+01 / [deg] ecliptic longitude of spin vector
PAR_BS  =              5.7E+01 / [deg] ecliptic latitude of spin vector
PAR_PSID=     3.1013433333E-01 / [days] spin period
PAR_T0  =              2.4E+06 / epoch if light curve zero-point
PAR_GAM0=              2.7E+02 / [deg] orientation at epoch T0
PAR_GALB=           6.0000E-02 / geometric albedo
PAR_EMVT=           8.9982E-01 / average emissivity
PAR_INRT=             1.50E+01 / thermal inertia (Gamma)
PAR_BMOD= 'beamsph '           / beaming model
PAR_B_S =           3.4885E-01 / beaming parameter S
PAR_B_F =           6.0000E-01 / beaming parameter f
PAR_H   =           7.1300E+00 / absolute magnitude H
PAR_G   =           1.0000E-01 / slope parameter G
PAR_R   =       2.05829323E+00 / [AU] heliocentric distance
PAR_DELT=       1.93029248E+00 / [AU] geocentric distance
PAR_PHAS=       2.93716025E+01 / [deg] phase angle
AUTHOR  = 'Mueller & Lagerros' / Authors of the thermophysical model
END
```