TNOs are Cool: A survey of the Transneptunian region
Radiometric properties of TNOs

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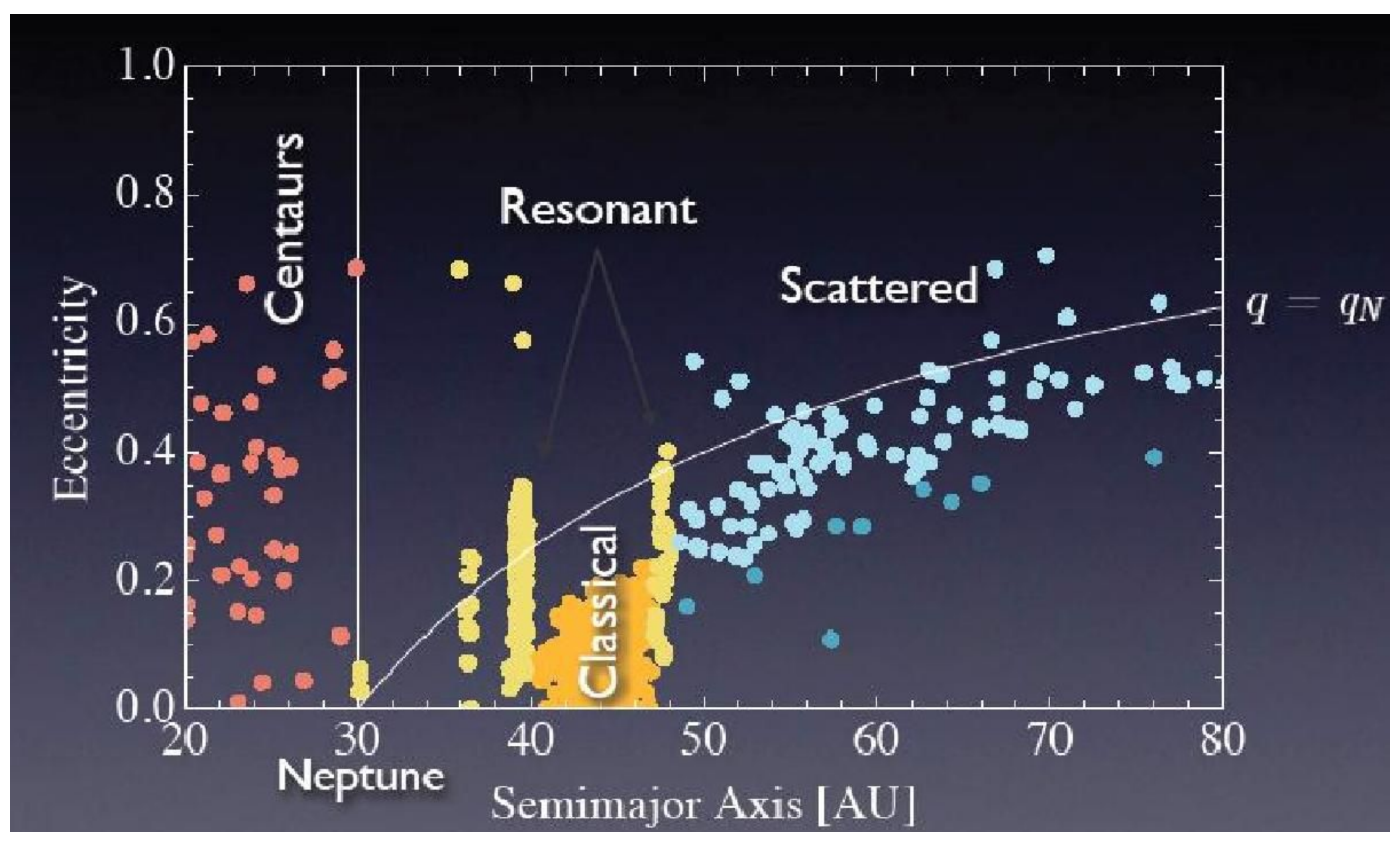
ABSTRACT

About 400 hours of observing time have been granted to the *Herschel* Open Time Key Programme “TNOs are Cool: A survey of the Transneptunian region” [1]. In this programme we are using photometric observing modes of the PACS [2] and SPIRE [3] instruments to obtain the fluxes of 138 objects representing different dynamical classes (resonant, classical, scattered disk and detached TNOs as well as Centaurs) and including 25 binary systems. Correlations between size, albedo, color, composition and orbital parameters are diagnostic of evolution processes. While *Spitzer* has revealed a large albedo diversity in the TNO population the increased wavelength coverage and sensitivity of *Herschel* will enable profound advances in this field. The four prime scientific goals of this programme are: (i) to determine sizes and albedos, (ii) to measure the density of binary TNOs, (iii) to constrain surface properties (without knowledge of albedos spectroscopy of surface compounds is semi-qualitative), and (iv) to determine lightcurves of six objects by continuously observing them throughout an entire rotational period. Our first results, based on combined data from *Herschel* and *Spitzer* as well as visual magnitudes from our ground-based support programmes, provide effective diameters, geometric albedos and thermal inertias of Haumea, Orcus, Makemake, Typhon, 2003 AZ_{84}, 2001 YH_{140}, 1997 CS_{29}, 2006 SX_{368} and 2005 TB_{190}. The Haumea lightcurve observed with PACS reveals a positive correlation between the optical and thermal lightcurves, indicating that they are due to shape effects.

INTRODUCTION

More than one thousand Trans-Neptunian objects (TNO) have so far been discovered, presumably remnants of the planetesimal disk. The size distribution of large TNOs is assumed to have remained unchanged, although their surface material has changed its composition over time due to impacts and space weathering. The red color of objects is a consequence of space weathering; it also makes surfaces darker. Objects having experienced recent impacts are expected to be brighter and bluer due to excavated un-weathered material.



Dynamical classification of TNOs

Thermal emission of an airless body depends primarily on its size, albedo and thermal inertia. Surface emissivity, roughness and porosity also influence the shape of the SED. The albedo and absolute reflectance are important in constraining the surface composition; this requires the combination of Herschel and ground-based support observations at optical wavelengths. Two major factors influence the light curves of these solar system objects: albedo features on the surface and the shape of the object. In the case of shape effects, the mean flux and amplitude are diagnostic of the distribution of temperatures on the object, thereby constraining the spin vector and the thermal inertia.

The fluxes of TNOs, with temperatures in the range 20-50 K, have their maxima in the PACS wavelengths (55 to 210 µm). Our flux estimates of the 138 targets at the PACS and SPIRE (194 to 672 µm) wavelengths are expected to range from a few mJy to 400 mJy.

ACKNOWLEDGEMENTS

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HERSCHEL SPACE OBSERVATORY

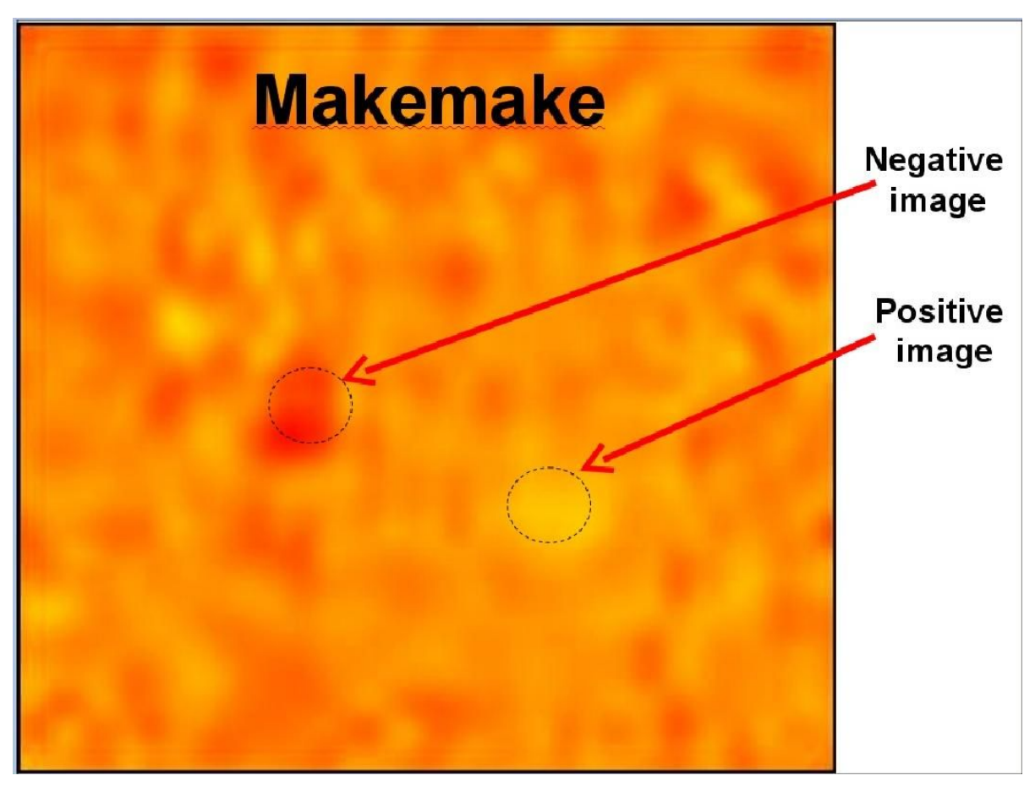
The *Herschel Space Observatory* is the largest infrared space observatory built to date. It was launched on May 14 2009 and will spend a nominal mission lifetime of three years in orbit around the second Lagrange point of the Sun-Earth system (L2).

The *Herschel* telescope is a Cassegrain design with a primary mirror diameter of 3.5 metres. The three scientific instruments are:

- **HIFI** (Heterodyne Instrument for the Far Infrared), a very high resolution heterodyne spectrometer (157-625 µm)
- **PACS** (Photodetector Array Camera and Spectrometer) an imaging photometer and medium resolution grating spectrometer (55-210 µm)
- **SPIRE** (Spectral and Photometric Imaging Receiver) an imaging photometer and an imaging Fourier transform spectrometer (200-670 µm)

The 'TNOs are Cool'-project makes use of the PACS and SPIRE instruments.

Herschel/PACS observations produce a map with a spatial resolution of 1“-2“ per pixel and 50“ diameter area useful for photometry, whereas *Herschel*/SPIRE produces a map of 5' diameter. A typical on-source time per target is about 0.5 h, except for lightcurve targets which are observed several hours to cover more than one rotational period.



Herschel/SPIRE observations of the dwarf planet Makemake. This map is a positive/negative combination of two observations following each other after 43 hours, each of the maps was a combination of two cross scan maps composed of 12 parallel scans. The flux at 250 µm is (9.5+/-3.1) mJy.

OUTLOOK

Within our 'TNOs are Cool' programme we will observe about 140 TNOs and the results are expected to provide a benchmark for understanding the solar system debris disk, and extra-solar ones as well. We will observe 25 binary TNOs as well as the lightcurves of Varuna, Haumea, 2003 VS_2, and 2003 AZ_{84} for more than one rotational period. By September 2010 we will have *Herschel* observations for about 80 targets, including detailed studies of the most prominent dwarf planets Pluto, Eris, Haumea and Makemake.

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THERMAL MODELLING

Optical data alone are not sufficient to derive physical properties of unresolved bodies in the solar system. Additional data in the form of thermal IR data allow the use of thermal modelling to derive the size and albedo of an object. These models calculate the temperature distribution on the object's surface. Using Planck's equation the spectral energy distribution of the model body is computed and fitted to the observational data.

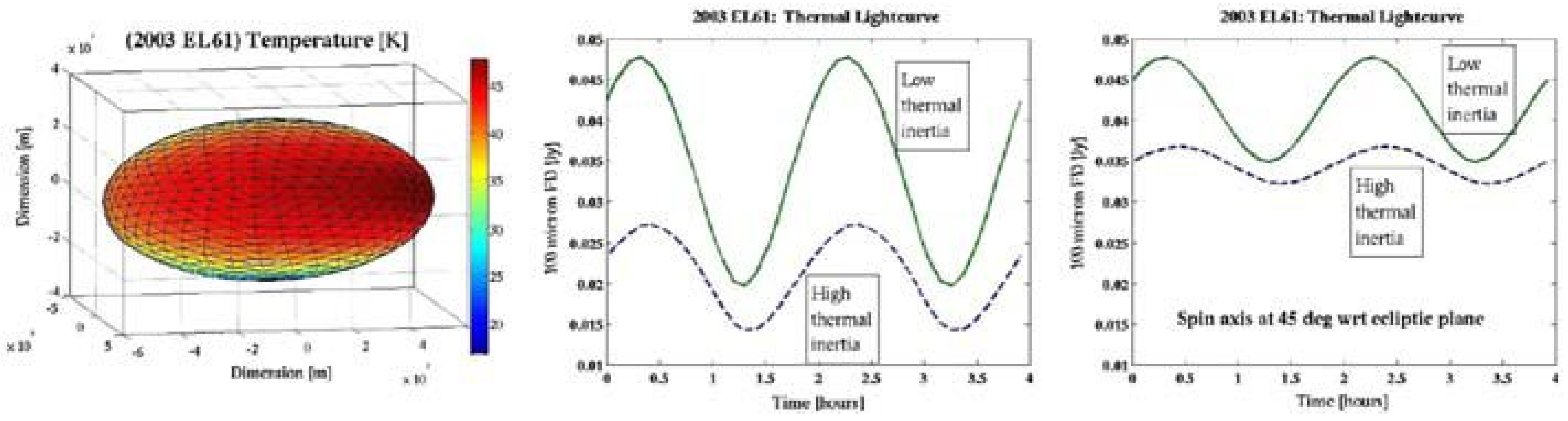
The models used in this project are:

- **STM**: spherical shape, smooth surface, slow rotation, low thermal inertia; needs an empirical *beaming parameter eta* to debias temperature distribution [4]
- **FRM**: spherical shape, smooth surface, fast rotation, high thermal inertia [10]
- **NEATM**: similar to STM but uses the beaming parameter eta to adjust the subsolar temperature and therefore to fit the model's spectral distribution to the thermal IR measurements [6]

Thermal models are rather simple but require only few data points. They are well tested even on TNOs [9].

THERMOPHYSICAL MODELLING

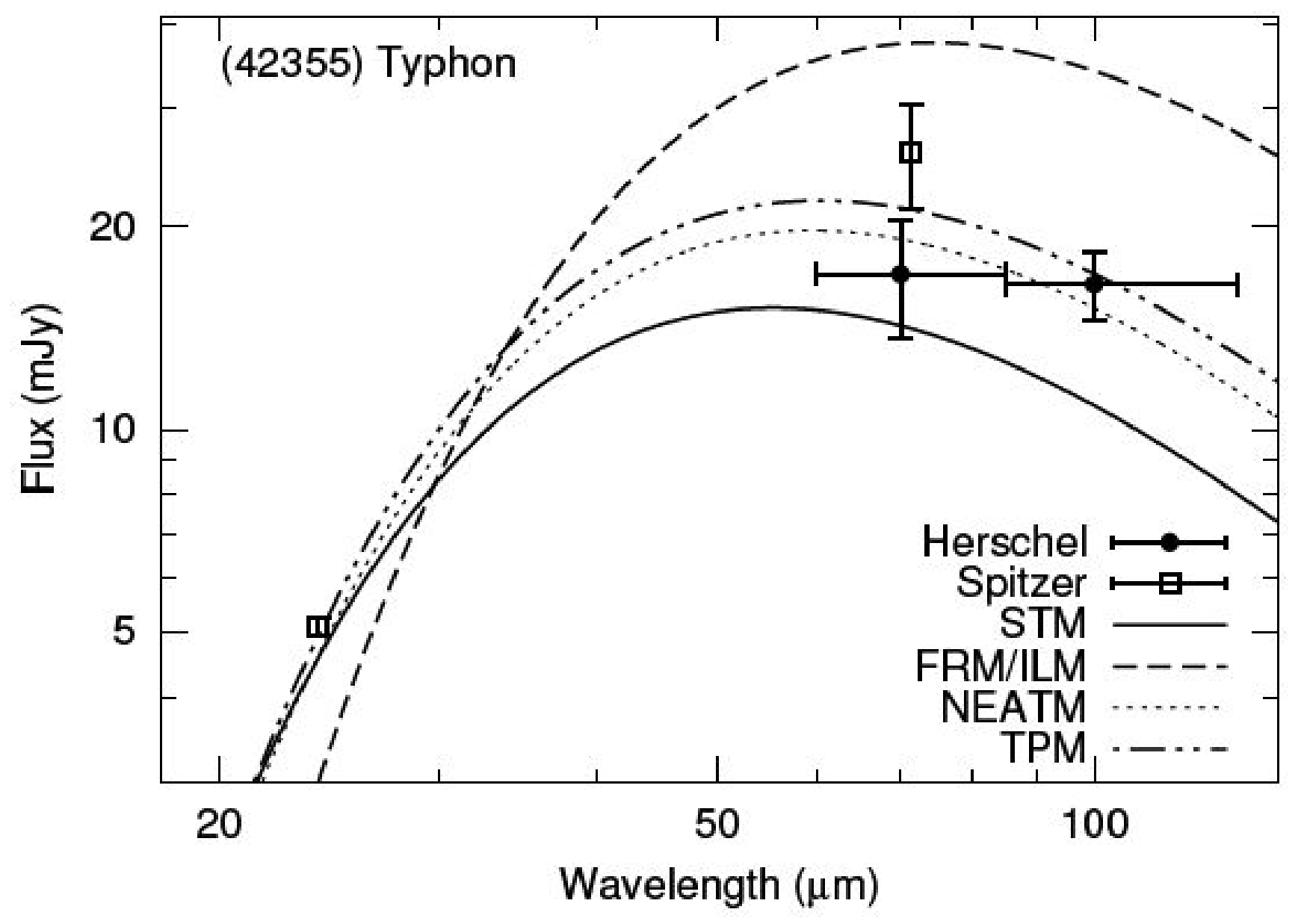
Thermophysical models are more realistic in a sense that they introduce effects like surface roughness and thermal inertia in the modelling process. This takes heat transfer via heat conduction and emission as well as multiple reflections at the surface into account. Furthermore, **TPM**s are more flexible regarding the model's shape and surface characteristics. [7], [11], [12]
However, TPMs require more information on the object like spin axis orientation, spin period and surface characteristics, which are usually not available for TNOs and therefore have to be assumed.



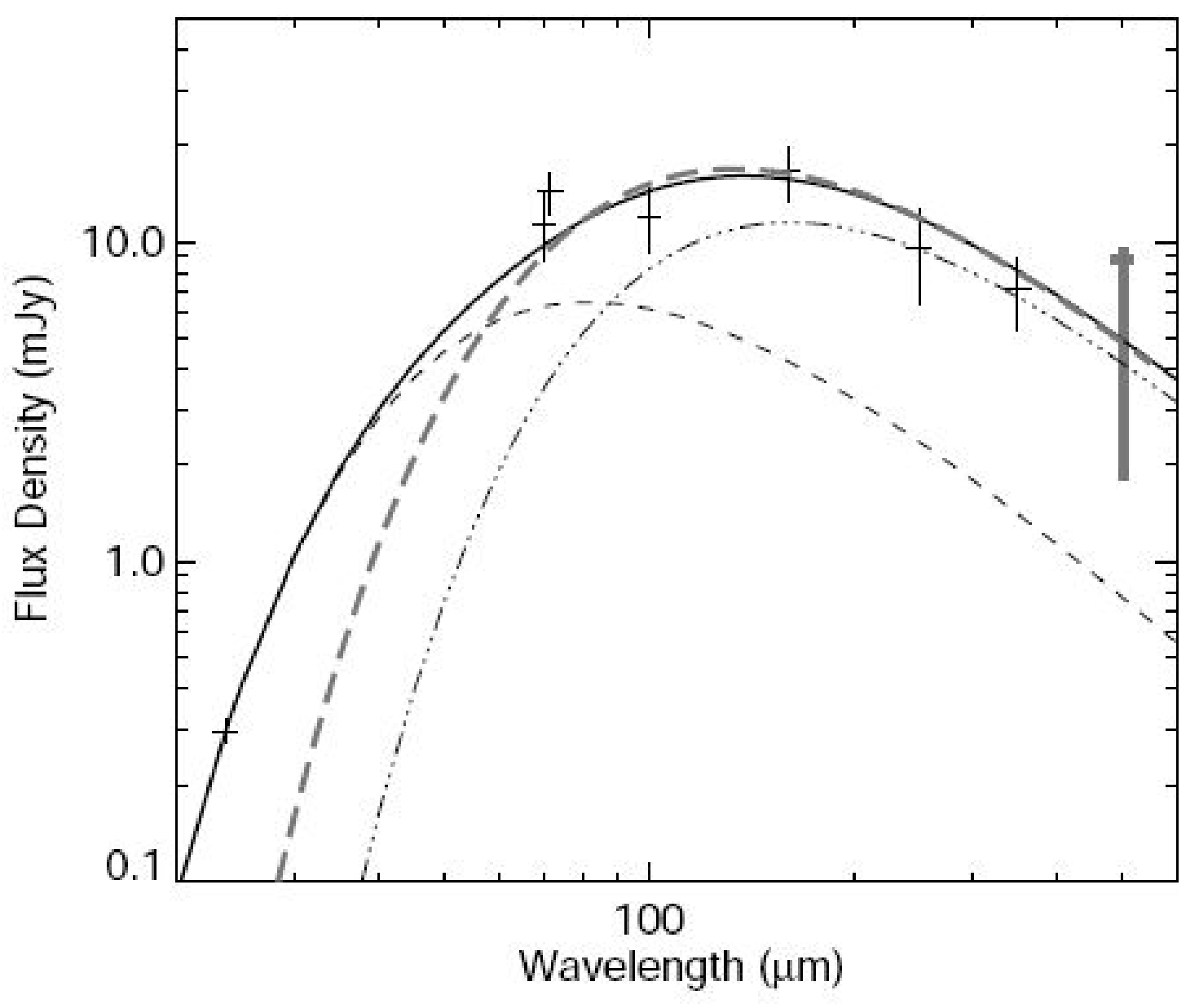
Thermophysical temperature calculation for Haumea (shape model [8]) as seen from *Herschel* with thermal properties based on *Spitzer* data [9]. Based on this model thermal lightcurves can be predicted and the effects of surface properties, spin vector orientation and wavelength can be studied. The middle figure shows Haumea's thermal lightcurve at 100 µm with a spin vector perpendicular to the ecliptic plane, and the right figure shows the same with spin axis at 45° angle.

RESULTS

Here we present the first results from the completed *Herschel* Science Demonstration Phase.



Thermal and thermophysical model fits for **Typhon**; it is obvious that the STM and FRM fit the observational data only poorly; NEATM and the TPM, however, fit very well and lead to similar results (cf. table below) [13]



Two-terrain model for **Makemake** [15]

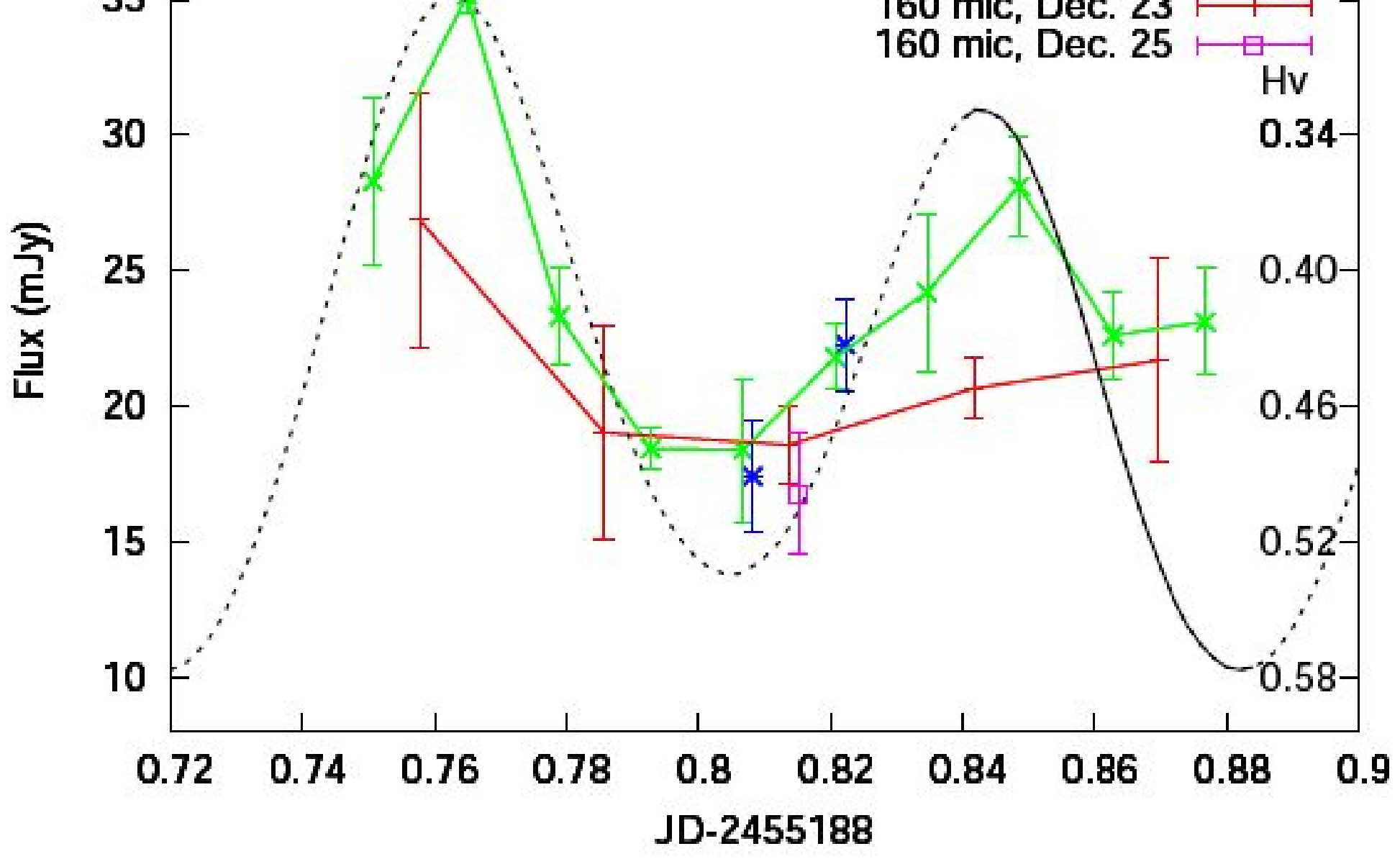
- bold dashed line: one-terrain model fit
- dashed line: emission from low-albedo terrain (p_V=0.04, eta=0.43, 3-7% surface coverage)
- dash-dotted line: emission from high-albedo terrain (p_V=0.9, eta=1.9, 93-97% coverage)
- continuous line: emission for two-terrain model

Overview

	phase	NEATM			TPM		
Target	angle [°]	D [km]	p_V [%]	*eta*	D [km]	p_V [%]	T.I. [SI]
2003 AZ_{84}	1.11	896 ± 55	6.5 ± 0.8	1.31 ± 0.08	850 – 970	5 – 9	2 – 10
2001 YH_{140}	1.44	349 ± 81	8 ± 5	1.2 fix	300 – 390	6 – 10	0 – 10
1997 CS_{29}	1.27	402 ± 69	6 ± 2	1.2 fix	250 – 420	6 – 14	0 – 25
2000 YW_{134}	1.25	only upper flux limits			< 500	> 8	0 – 25
Typhon	2.84	138 ± 9	8 ± 1	0.96 ± 0.08	134 – 154	6.5 – 8.5	1 – 10
2006 SX_{368}	4.48	79 ± 9	5 ± 1	1.2 fix	70 – 80	5 – 6	0 – 40
2005 TB_{190}	1.17	375 ± 45	19 ± 5	1.2 fix	335 – 410	15 – 24	0 – 25
Orcus	1.19	867 ± 57	25 ± 0.03	0.97 ± 0.07	790 – 950	22 – 34	0 – 3

There is a good agreement between NEATM and TPM results in diameter and albedo; NEATM was applied using a floating eta fit whenever possible, in cases where that was not possible a fix value of eta=1.2 was applied (cf. [9]); 3 of these targets were observed by Spitzer before, results agree well [9]; data were taken from [13] and [15]

Haumea thermal lightcurve



Haumea lightcurve observed with PACS 100 and 160 µm channels. The 100 µm thermal lightcurve is clearly positive correlated with the optical lightcurve (dashed and continuous black line) with an amplitude of factor 2 while the optical lightcurve has an amplitude of factor 1.3. This confirms that the lightcurve effects are due to shape.
A 160 µm lightcurve is marginally detected. The quality of the thermal data is not sufficient to clearly detect the effects of a surface dark spot (indicated in the optical lightcurve by the continuous segment). [14]