TNOs are Cool: A survey of the trans-Neptunian region - Herschel observations and thermal modeling of large samples of Kuiper belt objects

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Abstract

About 400 hours of *Herschel Space Observatory* observing time have been used by the Open Time Key Programme "TNOs are Cool: A survey of the trans-Neptunian region" [1]. In this programme we use photometric observing modes of the PACS [2] and SPIRE [3] instruments to obtain the far-infrared fluxes of 132 objects representing different dynamical classes (resonant, classical, scattered disk and detached TNOs as well as Centaurs) and including 25 binary systems. As leftovers of the formation of the Solar System [4] TNOs and their physical properties provide constraints to the models of formation and evolution of the various dynamical classes. The four main scientific goals of this programme are: (i) to simultaneously measure sizes and albedos, (ii) to measure the density of binary TNOs, (iii) to constrain surface properties, and (iv) to determine lightcurves of four objects by continuously observing them throughout an entire rotational period. We have published new diameter/albedo results for 60 targets based on our *Herschel* observations combined with data from the earlier *Spitzer* mission when available as well as with ground-based observations for more accurate absolute visual magnitudes. Diameter and albedo were measured for the first time for almost half of our published targets. Our analysis so far has concentrated mainly on classical TNOs, Plutinos and SDOs, whose average albedos and diameter characteristics have been estimated and possible correlations between physical and orbital parameters have been seeked [P IV - P VI]. We also show results of the potential Oort cloud object Sedna [P VII] as well as the dwarf planets Makemake [P III] and Haumea [P II].

1. Introduction

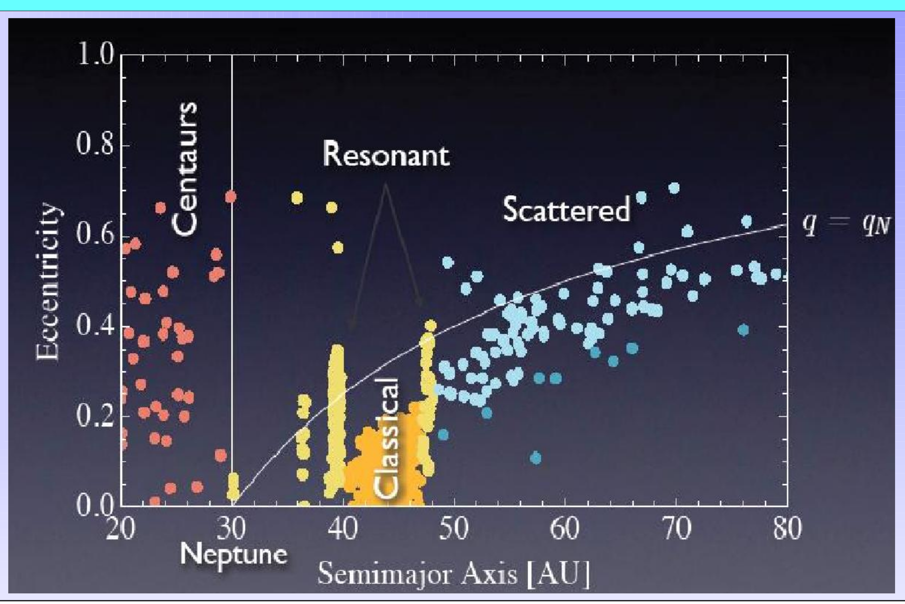
About 1600 Trans-Neptunian objects (TNO) and Centaurs have so far been discovered in our Solar System. They are remnants of the planetesimal disk and analogues to the parent bodies of dust in debris disks around other stars [5,6]. The size distribution of large TNOs is assumed to have remained unchanged although their surface material may have changed its composition over time due to collisions, meteorite/micrometeorite impacts and space weathering. 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.

Thermal emission of an airless body depends primarily on its size and albedo. Surface emissivity, roughness and porosity also influence the shape of the spectral energy distribution (SED). The albedo and absolute reflectance are important in constraining the surface composition. Without absolute reflectance the results from spectroscopy are semi-quantitative (see [7] for an example of using *Herschel* data in the spectroscopy of 2002 VE_{95}).

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 132 targets at the PACS and SPIRE (194 to 672 μm) wavelengths range from a few mJy to 400 mJy. Thermal and thermophysical models (STM [8], FRM/ILM [9], NEATM [10], TPM [11]) provide sizes and albedos, and they also give indications on the surface properties.

Lightcurves (LC) are influenced by two major factors: albedo features on the surface and the shape of the object. In the case of shape effects the optical and thermal Lcs are correlated and the mean flux and amplitude are diagnostic of the distribution of temperatures on the object, thereby constraining the spin vector and the thermal inertia. Albedo features on the surface produce a thermal LC, which is anti-correlated with the optical LC. Large TNOs (radius >100 km) may have the primordial distribution of angular momenta whereas smaller objects have had their spins, shapes and sizes collisionally altered.

2. Orbits of our sample



3. Herschel observations

From PACS instrument's (bolometer array pixels 3.2"x3.2" at 70 and 100 μm and 6.4"x6.4" at 160 μm) observations we produce maps with a spatial resolution of 1"-2"/map-pixel. An area of 50" in diameter is useful for photometry. A typical total on-source time/target is about 0.5 h (double in the 160 μm channel), except for lightcurve targets which are observed several hours. For 11 targets observed also with SPIRE (beam sizes of feedhorn-coupled detectors 18.1"/25.5"/36.6" at 250/350/500 μm) we produce maps of 5' in diameter with a resolution of 6"-14"/map-pixel. A follow-on observation at a different sky background while the target is still within the map of the first observation is a useful strategy at wavelengths higher than 100 μm in order to remove the background features and enhance the signal-to-noise ratio.

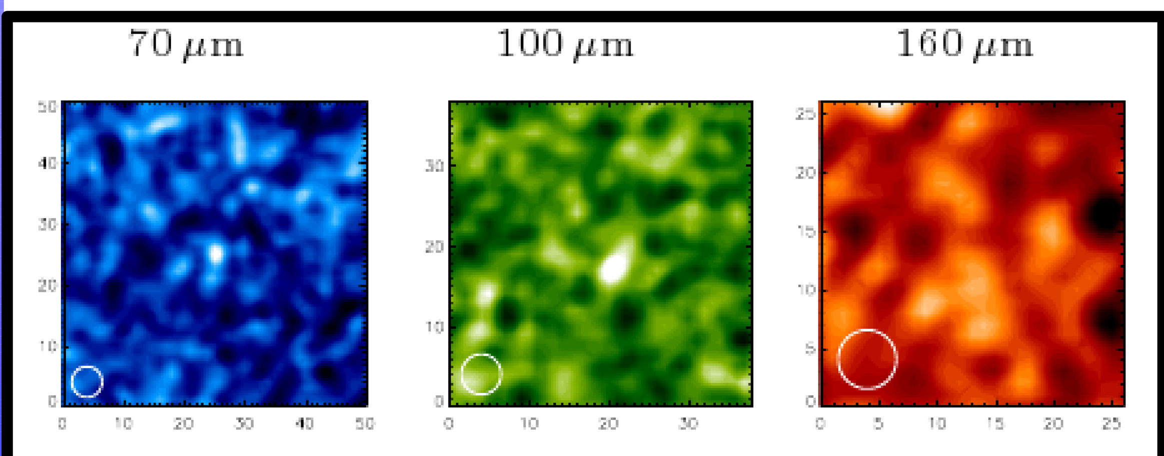
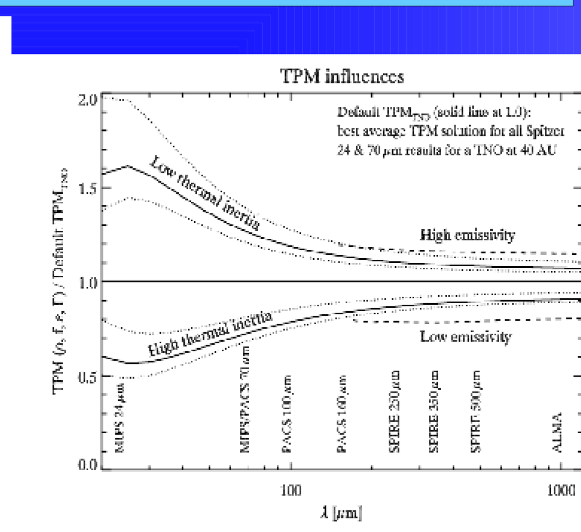


Fig 1. First thermal detection of Sedna (at the center of each map) from maps composed of 8 individual observations at two epochs [P VII]. Sedna is one of our faintest targets with flux densities of 1.8 / 4.2 / 2.7 mJy in the three PACS bands. The effective beam size is shown as a circle in the lower-left corner.

4. Thermal modeling

Model calculations of the Thermophysical Model (TPM) compared to an average *Spitzer* TNO at 40 AU to demonstrate the influence of surface properties on the thermal flux. The thermal inertia causes major uncertainties at wavelengths below the emission peak while the unknown emissivities affect the sub-mm range where also the influence of extreme surface conditions is seen (dashed lines).



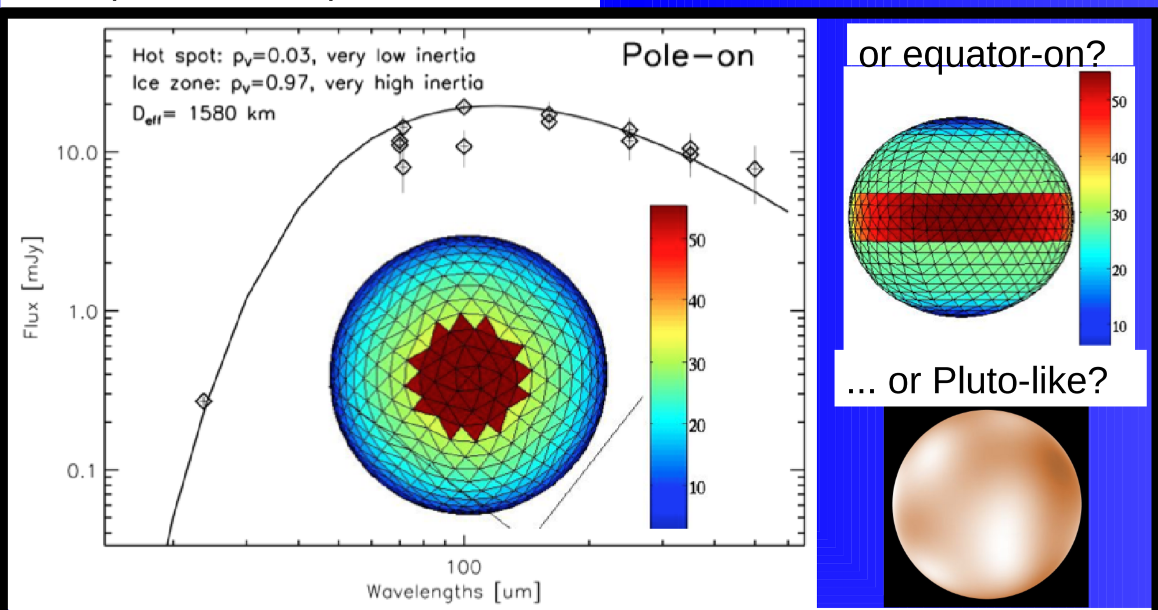


Fig 2. Thermophysical modeling of Makemake. The object was observed twice with PACS (70, 100 and 160 μm) and SPIRE (250, 350, 500 μm) instruments of *Herschel* as well as with *Spitzer* (24 and 71 μm). 2 or more albedo terrains are required to fit all data points: (i) a low-albedo hot zone with low thermal inertia and high roughness, possible dusty, porous ice surface, and (ii) a high-albedo, high thermal inertia and low roughness cold zone, possible of freshly condensed, compact methane ice. Another explanation instead of the 2-terrain model could be a dark, not yet detected, moon of Makemake.

5. Lightcurve of Haumea

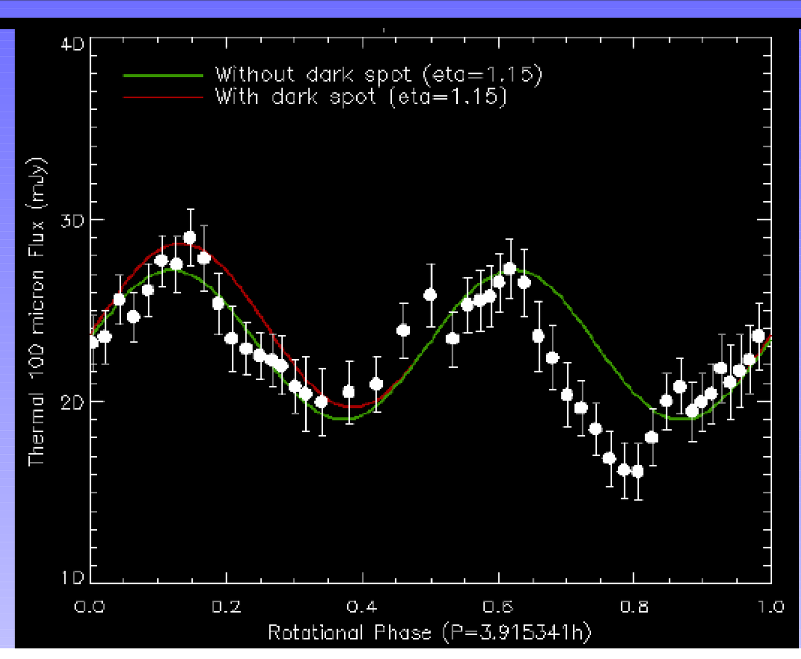


Fig. 3. Haumea lightcurve observed twice with PACS 100 μm channel and a modeled LC [12] with and without a dark spot (shape model 2 in P II). The thermal and visible lightcurves are correlated (shape effect) with a factor of variation 2 in thermal and 1.3 in visible. We find no clear evidence of a dark spot. Thermal inertia is very low and the surface is porous.

6. Sample results

Table 1. Results of sub-samples. D: effective radiometric diameters of objects or systems (if binary), p_V: geometric albedos.

Ref.	Class	Number of targets	D range (km)	p_V range (%)	Average p_V (%)
P IV	Scattered disc	8	110–1300	4–19	6.9 ± 3.4
P IV	Detached object	6	$250–600^a$	$8–33^a$	17 ± 7.7^a
P V	Plutino	17	150-730	4–28	8 ± 3
P VI	Classical / cold	6	140–340	4–22	17 ± 4
P VI	Classical / hot	12	100–930	4–20	9 ± 5
P VII	Sedna	1	995 ± 80	32 ± 6	...

Notes. $^{(a)}$ Excluding Eris.

Table 2. Bulk densities of binary systems. D: effective radiometric diameter.

Ref.	Target	Class	System D (km)	Density (g/cm^3)
P VI	Teharonhiawako	Classical / cold	177^{+46}_{-44}	1.14
P IV	Typhon	Scattered disc	185 ± 7	0.36
P VI	2001 XR_{254}	Classical / cold	200^{+49}_{-63}	1.4
P VI	2001 QY_{297}	Classical / cold	200^{+62}_{-59}	1.4
P VI	Altjira	Classical / hot	257^{+90}_{-92}	0.63
P IV	Ceto	Scattered disc	281 ± 11	0.64
P VI	Sila	Classical / cold	343 ± 42	0.73 (see also [13])
P V	1999 TC_{36}	Plutino	$393.1^{+25.2}_{-26.8}$	0.64
P VI	Salacia	Classical / hot	901 ± 45	1.38
P IV	Eris	Detached object	2454 ± 117	2.40

Table 3: Selected correlation results. q: perihelion distance.

Ref.	Class	D vs p_V	p_V vs q	D vs q
P IV	Scattered+Detached	pos.	pos.	pos.
P V	Plutino	no	no	no
P VI	Classical / hot	neg.	no	no

Our small sample of **(S)DOs** shows two correlations: 1. More reflective objects are larger, probably because large objects can retain bright ices more easily than small objects. However, we do not see this in other dynamical classes; 2. Brighter and larger SDOs have larger perihelia. The p vs q correlation has been explained by increased ice sublimation and/or space weathering at low heliocentric distances [14]. In the **Plutino** sample there is a correlation between D and the heliocentric distance at the time of discovery, but not with p, which indicates a size-dependent discovery bias [P V].

Size distributions / cumulative power laws

* Plutinos at D=120-400 km have a slope parameter 2 and larger sizes 3.

* Hot classicals at D=100-600 km have a slope parameter of 1.4.

Publications from "TNOs are Cool: A survey of the Trans-Neptunian region"

[P I] Müller, Lellouch, Stansberry et al., A&A, 518, L146, 2010
"I. Results from the *Herschel* Science Demonstration Phase (SDP)"

[P II] Lellouch, Kiss, Santos-Sanz et al., A&A, 518, L147, 2010
"II. The thermal lightcurve of (136108) Haumea"

[P III] Lim, Stansberry, Müller et al., A&A, 518, L148, 2010
"III. Thermophysical properties of 90482 Orcus and 136472 Makemake"

[P IV] Santos-Sanz, Lellouch, Fornasier et al., A&A, 541, A92, 2012
"IV. Size/ albedo characterization of 15 scattered disk and detached objects observed with Herschel Space Observatory"

[P V] Mommert, Harris, Kiss et al., A&A, 541, A93, 2012
"V. Physical characterization of 18 Plutinos using Herschel/PACS observations"

[P VI] Vilenius, Kiss, Mommert et al., A&A, 541, A94, 2012
"VI. Herschel/PACS observations and thermal modeling of 19 classical Kuiper belt objects"

[P VII] Pal, Kiss, Müller et al., A&A, 541, L6, 2012
"Size and surface characteristics of (90377) Sedna and 2010 EK_{139}"

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