The trans-Neptunian Objects after *Herschel*: What Could *SPICA* Add to the Understanding of the Kuiper Belt?

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ABSTRACT

About 400 hours of the *Herschel Space Observatory*'s time has been used by the Open Time Key Programme "TNOs are Cool: A survey of the trans-Neptunian region" to obtain PACS (70, 100 and 160 μm) and SPIRE (250, 350 and 500 μm) photometry of 132 objects representing different dynamical classes (resonant, classical, scattered disk and detached TNOs as well as Centaurs), including 25 binary systems. As leftovers of the formation of the Solar System TNOs and their physical properties provide constraints to the models of formation and evolution of the various dynamical classes. *SPICA* is going to be a main leap forward on the way that *Herschel* started in the characterization of TNOs by determining size, albedo and other surface properties. *SPICA* is going to cover the mid- to far-IR wavelengths where TNO SEDs peaks (currently covered with *Herschel*/PACS and *Spitzer*/MIPS together). While *Herschel* could observe about 10 % of the known TNOs, with its increased sensitivity *SPICA* would be able to detect most (probably all) currently known TNOs. The observing strategy we used in our key program will also be relevant for *SPICA* observations to beat the confusion noise.

1. INTRODUCTION

Transneptunian Objects (TNOs) are believed to represent one of the most primordial populations in the Solar System. TNOs, as any other small bodies, are part of the ancient and today very tenuous debris disk of our Solar System. This population — that includes various subpopulations with different orbital characteristics — is particularly interesting since similar "Kuiper-belt-like" debris disk are often found around other stars, although usually at a different age and brightness than in our Solar System. The major difference between these disks and our Kuiper belt is that in the case of exosolar systems we are just able to observe the smallest sizes, the thermal emission from microscopic dust grains. In our Solar System, however, we are unable to detect this dust component (mostly due to the strong foreground, the Zodiacal emission), but we can study a significant fraction of larger bodies — this cannot be done in other planetary systems. As the surface temperatures of Kuiper-belt objects are in the order of 40–50 K, their thermal emission peaks in the far-infrared. This made the PACS and SPIRE cameras of the *Herschel Space Observatory* (Pilbratt et al. 2010) especially suitable to survey the trans-Neptunian region. In the "TNOs are Cool!" Open Time Key Program (Muller et al. 2009) we aimed to obtain sizes, albedos, surface thermal properties, etc. of a large sample of trans-Neptunian objects and characterizing our debris disk for the first time and these kind of information cannot be derived from visual range measurements only.

2. *HERSCHEL* OBSERVATION DESIGN AND DATA REDUCTION STRATEGIES

Confusion noise is a major limiting factor for the observations of faint targets in the far-infrared (see e.g. Kiss et al. 2005). Despite its large primary mirror compared to previous space infrared telescopes like the *Infrared Space Observatory* and the *Spitzer Space Telescope*, even the measurements with the *Herschel Space Observatory* were limited by confusion noise, especially at the longer photometric wavelengths (160 μm and above). Confusion noise due to the extragalactic background and Galactic cirrus will be very similar in the case of *SPICA* to that seen by the *Herschel Space Observatory* due to the similar primary mirror size and resolution power of the two telescopes.

In the "TNOs are Cool!" OTKP we paid a special attention to confusion noise. First, we selected those observation dates for our TNOs are Centaurs when the expected confusion noise due to the background was the possible smallest during their motion in the sky (Kiss et al. 2005; Kiss 2007). In addition, we used multiple epoch observations — the way these observations were combined was very effective in eliminating the background and hence the confusion noise. All our observations were processed with a dedicated pipeline, optimized for these faint targets. Special techniques were used

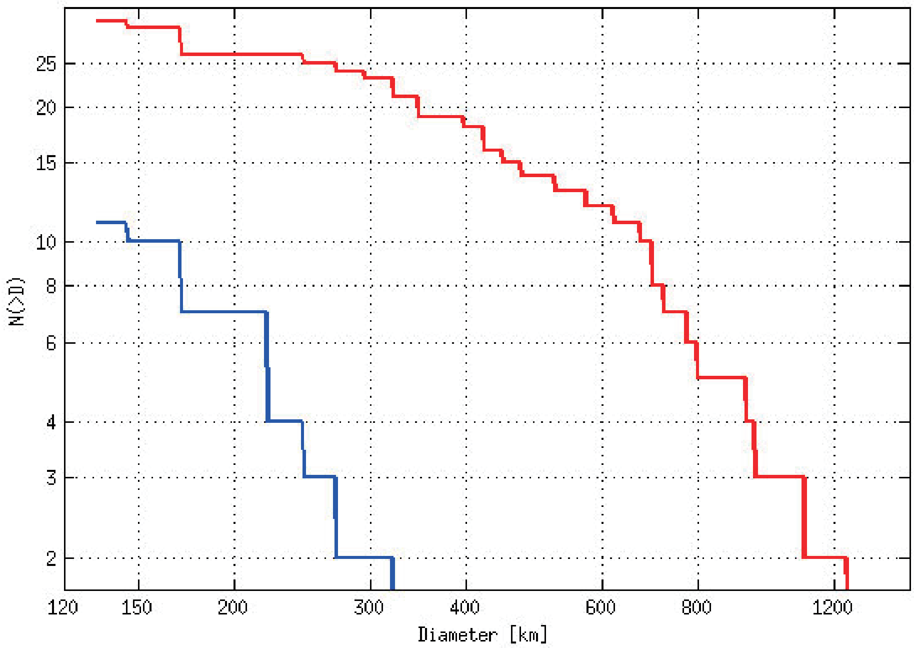

Figure 1. Size distribution of hot (*red*) and cold (*blue*) classical trans-Neptunian objects (Vilenius et al. 2013).

to correct for errors originated from pointing differences of the telescope as well as for relative positional uncertainties. All observation design and data reduction techniques are discussed in detail in our dedicated paper (Kiss et al. 2013).

A good majority of our targets (>90 %) are detected in at least one band (in the blue band in almost all cases), about 50 % of them are detected in all the three PACS bands. With our techniques we managed to reach 0.6, 0.9 and 1.6 mJy flux uncertainties using the combined products of 5-repetition single maps in the 70, 100 and 160 μm PACS bands, respectively, with a total integration time of ~90 min at the shorter PACS wavelengths and ~180 min in the 160 μm band.

As the confusion noise could be very effectively eliminated with our techniques, the final limitation is the instrument noise in our OTKP. Using our observation and data reduction strategies, a similar survey with *SPICA* would be able fully exploit the superior capabilities of the detectors planned (Nakagawa et al. 2011).

3. MAIN *HERSCHEL* SCIENCE RESULTS AND THE PERSPECTIVES FOR *SPICA*

3.1. Thermal Properties

The investigation of the thermal properties of TNOs are Centaurs (Lellouch et al., 2013) revealed that beaming factors (η) range from values of <1 to ~2.5, but we are lacking large values at small heliocentric distances. The mean thermal inertia in the population is found to be $\Gamma = (2.5 \pm 0.5)\,\mathrm{J\,m^{-2}\,s^{-1/2}\,K^{-1}}$, and there is a strong suggestion that the thermal inertia decreases with heliocentric distance The observed thermal inertias are 2–3 orders lower than expected for compact ices and are generally smaller than on Saturn's satellites or in the Pluto/Charon system. Objects with high albedos (>20 %) have lower beaming factors than the rest of the population, i.e. they have unusually low thermal inertias. This possibly results from smaller grain size. An exception is Makemake. The ensemble of our results suggests strongly porous surfaces, in which the heat transfer is affected by radiative conductivity within pores and increases with depth in the subsurface.

To obtain thermal properties from infrared measurements in the sample above, the target has to be clearly detected at several wavelengths. As was mentioned, this was not the case with our *Herschel*/PACS sample that limited the number of objects that such a study could be performed for. The higher sensitivity of *SPICA* at these wavelengths will allow the determination of thermal properties for a larger number of targets and will certainly probe the small end of the size distribution. These smaller targets may have thermal properties significantly different from those in our current sample, revealing different formation and evolution scenarios.

3.2. Size Distribution

On of the most important global characteristic of a debris disk it its size distribution. In our OTKP we sampled all major populations of the trans-Neptunian region: Classicals, Plutinos, Scattered disk and detached objects, resonant TNOs, and Centaurs, too. We could derive the main characteristics of these populations, like the slope parameter of the size distribution. E.g. Plutinos at D = 120–400 km have a slope parameter of 2, and at larger sizes of 3 (Mommert et al. 2012). Hot classicals at D = 100–600 km have a slope parameter of 1.4, based on a smaller sample (Vilenius et al. 2012).

In the extended sample (Vilenius et al. 2013) hot Classicals have a larger maximum size and therefore a wider part of the distribution is observed. The difference in the distributions is compatible with the hypothesis that hot Classicals were formed in a region where the surface mass density was higher than in the case of cold Classicals.

3.3. Surface Characteristics of Scattered Disk and Detached Objects

Our sample of Scattered disk and detached objects shows two interesting correlations. 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; The other interesting feature is that brighter and larger SDOs have larger perihelia. This correlation has been explained by increased ice sublimation and/or space weathering at low heliocentric distances (Santos-Sanz et al. 2012).

4. CONCLUSIONS

The "TNOs are Cool!" Open Time Key Program was very effective in measuring the thermal emission of Centaurs and TNOs that revealed many important individual characteristics of specific targets, and also allowed us to derive such properties of the Kuiper belt populations that were not known before. However, *Herschel* could just observe a rather limited sample and it could only be *SPICA* (with the capability of observe almost 100 % of the presently known TNOs) in the relatively near future that would be able to extend the limits of our OTKP in order to better understand the evolution of our own Solar System as well as that of exo-solar debris systems.

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