TNOs are Cool: A Survey of the Transneptunian Region

A Herschel Open Time Key Programme

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Abstract Over one thousand objects have so far been discovered orbiting beyond Neptune. These trans-Neptunian objects (TNOs) represent the primitive remnants of the planetesimal disk from which the planets formed and are perhaps analogous to the unseen dust parent-bodies in debris disks observed around other main-sequence stars. The dynamical and physical properties of these bodies provide unique and important constraints

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on formation and evolution models of the Solar System. While the dynamical architecture in this region (also known as the Kuiper Belt) is becoming relatively clear, the physical properties of the objects are still largely unexplored. In particular, fundamental parameters such as size, albedo, density and thermal properties are difficult to measure. Measurements of thermal emission, which peaks at far-IR wavelengths, offer the best means available to determine the physical properties. While *Spitzer* has provided some results, notably revealing a large albedo diversity in this population, the increased sensitivity of *Herschel* and its superior wavelength coverage should permit profound advances in the field. Within our accepted project we propose to perform radiometric measurements of 139 objects, including 25 known multiple systems. When combined with measurements of the dust population beyond Neptune (e.g. from the New Horizons mission to Pluto), our results will provide a benchmark for understanding the Solar debris disk, and extra-solar ones as well.

1 Introduction

Transneptunian Objects (TNOs) are believed to represent one of the most primordial populations in the solar system. The TNO population comprises (i) the main Kuiper Belt beyond the orbit of Neptune (~ 32–50 AU), consisting of objects in resonant and non-resonant orbits, and (ii) the halo outskirts of "scattered" and "detached" bodies beyond 50 AU. The Centaurs, an unstable orbital class of minor planets, are closer to the Sun and in transition from the Kuiper Belt towards the inner solar system (where some of them are

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eventually captured as short-period comets in the Jupiter family). More than 1300 TNOs have been detected so far revealing a rich orbital structure and intriguing physical properties. These TNOs represent only a few percent of the estimated 30,000 TNOs brighter than 24 mag in the visible.

The TNOs are the frozen leftovers from the formation period of the outer solar system (Morbidelli et al. 2008). The current total mass in the Kuiper Belt is estimated to be around 0.03–0.3 Earth masses (Trujillo et al. 2001), but there is evidence that a much larger mass ($\sim 10 - 40\,M_\oplus$) was originally present at the time of formation (Kenyon and Luu 1998). The Transneptunian population is analogous to the debris disks observed around several other, 10–500 Myr old stars. This analogy is bolstered by similarities in sizes and observed masses (typically 30–300 AU and $0.01 - 0.1\,M_\oplus$ for the "exo-disks"), with the important difference that the detected mass in extra-solar debris disks is in the form of ~ 10–1000 μm, short-lived, dust particles. The vast majority of the mass in such disks is invisible to us, probably in the form of kilometer (or more)-sized bodies, resembling Transneptunian objects. These objects serve as parent bodies from which the dust is generated by collisions.

Herschel (to be launched in 2009) is set up to make a key contribution to the study of the "Cool Universe" (Pilbratt 2008). The continuum emission emanating from bodies with temperatures between 5 and 50 K peak in the Herschel wavelength range. Among other science goals, *Herschel* was designed to observe dusty debris disks around other stars. Our accepted Key Programme will concentrate on the study of our own debris disk, the only case in which the parent bodies are currently accessible to direct observations.

2 Goals of the Observations

Because TNOs are cold (20–50 K), their thermal flux peaks in the spectral range to be covered by *Herschel* (see Fig. 1, left side). Our project includes accurate, multi-colour flux measurements for about 140 objects with PACS, the **P**hotodetector **A**rray **C**amera and **S**pectrometer in the wavelength range 55–210 μm (Poglitsch et al. 2008) and SPIRE, the **S**pectral and **P**hotometric **I**maging **RE**ceiver, in the wavelength range 194–672 μm (Griffin et al. 2008). The four major science goals of our programme are described in the following sections.

2.1 TNO Sizes and Albedos

There are several fundamental motivations for measuring the sizes and albedos of a large sample of TNOs. *Firstly*, determining the sizes of 100+ objects will provide information

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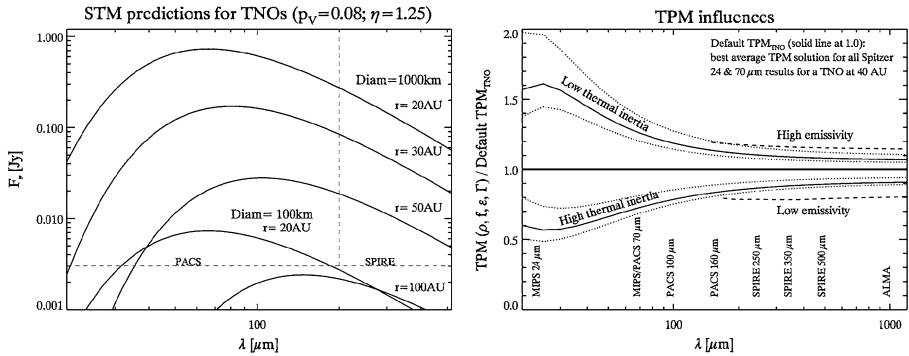
Fig. 1 *Left*: STM (standard model) flux predictions for a 1000 km TNO at different distances from the Sun. As input parameters we used the averaged *Spitzer*-values of 1.25 for the beaming parameter η and 0.08 for the geometric albedo p_V. For comparison, a 100 km TNO at 20 AU is shown together with a detection limit of 3 mJy. *Right*: Influence of the surface properties on the thermal flux, based on thermophysical model (TPM) calculations. We show here the ratio of the flux to what is expected from a "default TPM$_{TNO}$" model (best fit to all Spitzer TNO results). The thermal inertia causes major uncertainties at wavelengths below the emission peak, while the unknown emissivities affect mainly the sub-mm/mm range. The influence of extreme surface roughness conditions (perfectly smooth, or completely covered by craters) is indicated by the *dashed lines*

on the present and the original size distribution in the Kuiper Belt and constrain formation models. Objects detectable with *Herschel* will be typically 200 km or more in diameter. These larger TNOs should reflect the primordial-size distribution, in contrast to objects smaller than ~ 100 km which are slowly eroded by collisions (Farinella and Davis 1996). *Secondly*, the knowledge of the absolute albedo is a very important input parameter for scattering models which allow to constrain the surface composition (e.g., Pinilla-Alonso et al. 2009). Because pure ices are usually bright, a low albedo is indicative of a dark surface material (e.g. tholin, dark carbon) which is otherwise spectrally neutral. Modelling techniques (e.g. models by Hapke, Shkuratov and Muinonen, see Muinonen et al. 2002 and references therein) of surface spectra and polarimetry are available, potentially allowing a determination of the relative abundances of surface materials, grain size, and the state of mixing, but these can be applied only if the absolute reflectance is known, which will be extracted from combining Herschel data with ground based visible magnitudes. *Thirdly*, we anticipate that correlations between size, albedo, colour, composition and orbital parameters will be diagnostic of evolution processes. It is believed that the diversity of TNOs surface colours (from neutral to very red, i.e., from V–R ~ 0.35 to V–R ~ 0.75, respectively, where V and R are the apparent magnitudes in filters centered near 5500 and 6500 Å) are associated to different compositions, various surface evolution processes, impact events, and cometary activity. For example, from laboratory experiments, it appears that bright but spectrally neutral ices become optically red and dark as a result of ion radiation (one of the effects of space weathering), while a long-term exposure to ion flux darkens them further and neutralizes their spectral slope (Moroz et al. 2003, 2004). Furthermore, objects that have experienced a higher impact rate, or recent impacts, may be intrinsically brighter (and bluer), if collisions excavate fresh, un-weathered material from below the surface. If the colours tell us something fundamental about the bulk compositions, or if they merely reflect superficial processes acting on the optically accessible surfaces is unknown. Evidence for colour-orbit correlations in the Kuiper belt

(consequently for TNOs) is very limited. It is therefore necessary to measure the albedos of TNOs with well-determined colours and covering the full range of colours to shed light on these open questions.

2.2 Density Measurements

The bulk density is a key geophysical parameter containing information on the internal composition and structure, hence origin and evolution of TNOs (e.g., Noll et al. 2008b). In the case of rotationally deformed bodies, the density can be inferred from the visible lightcurve, assuming a "fluid" behaviour. For binaries (or multiple) systems, for which the total mass of the system is known, measuring the size (actually the equivalent diameter of the system) provides a determination of its mean density. To date, results from *Spitzer* are scarce, being limited to ~5 objects (Noll et al. 2008a). Surprisingly enough, the inferred densities span a very large range from ~0.5 to 3 g cm^{-3}. The high densities are indicative of large amounts of rocky materials. Along with the presence of surface ices, this would point to them being differentiated bodies. Very low densities require little or no rock in the interior, and imply considerable porosity.

Knowledge of the density offers a constraint on models of binary formation. For example, very high densities may reflect a collisional origin, in which the lighter outer mantle was torn away, as in the case of 136,108 Haumea (2003 EL$_{61}$). We will observe 25 binary systems, i.e. ~50% of the total number of known binaries and determine the size and, when combined with mass information, the average density for each.

2.3 TNO Surface Properties: Thermal Inertia, Surface Roughness, Emissivity

The thermal emission of KBOs depends not only on their size and albedo but also on unknown surface properties such as thermal inertia, spin state, surface roughness, and emissivity (Fig. 1, right side). When only single-wavelength measurements are available, not including these effects may lead to grossly inaccurate sizes and albedos (e.g. Harris and Lagerros 2002). However, if the objects are observed at two or more thermal wavelengths, these effects can be accounted for to first order by scaling the model surface temperature distribution with a "beaming factor", η, adjusted empirically to fit the observed colour temperature. As demonstrated in the case of TNOs by Stansberry et al. (2008), this approach allows a considerably improved albedo and diameter determination. Moreover, it gives insight into the object's *thermophysical* properties. For example, high values of η at small solar phase angles unambiguously indicate high thermal inertia and the lack of a dusty regolith, while a value much less than unity indicates a strong "beaming" effect due to surface roughness. This method, applied to the *Spitzer* two-colour (24 and 70 μm) measurements (when available), leads to a mean value of $\eta = 1.25$, but with extremely large scatter (Fig. 2) due to the large error bars on the individual measurements, and possibly due to a range of spin orientations, spin rates and thermal characteristics. While limited, these results outline the promise of such studies. Much better results are expected with *Herschel*. We will observe the majority of our targets in *three* PACS bands (70, 100, 160 μm), and with improved S/N. Although, for a given object, a physical interpretation of the η-values requires a knowledge of the spin state, the distribution of η-value will allow us to draw conclusions about the ensemble-averaged thermal properties of our targets (e.g. Delbo et al. 2007). In addition, for the 17 brightest objects, we will perform SPIRE measurements (250, 350, 500 μm) and expand the multi-wavelength photometry to 6 bands. In these cases we will also be able to determine the long wavelength emissivity.
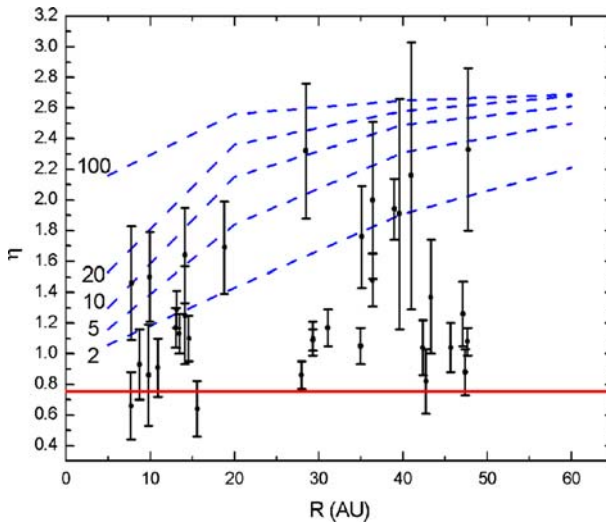
Fig. 2 Beaming factors from Spitzer observations versus heliocentric distance in AU. The *dashed curves* are model calculations for a spherical object with a rotation period of 2 h, rotation axis perpendicular to the solar direction, and thermal inertia of 2, 5, 10, 20, and 100 J m^{-2} $s^{-0.5}$ K^{-1}. The horizontal line at $\eta = 0.756$ corresponds to a theoretical lower limit for objects with zero thermal inertia, and/or sunward oriented spin axis, and surface roughness characteristic of large main-belt asteroids. The η values of a large set of objects with random spin vectors will be bounded by the horizontal line and one of the dashed curves. The largest η values at a given heliocentric distance are indicative of the largest values of thermal inertia. The smallest η values can provide information on surface roughness. While the large error bars limit the information available in the case of Spitzer data, the plot illustrates how an analysis of the distribution of η values derived from Herschel data can provide information on the thermophysical properties of our targets and their possible variation with heliocentric distance
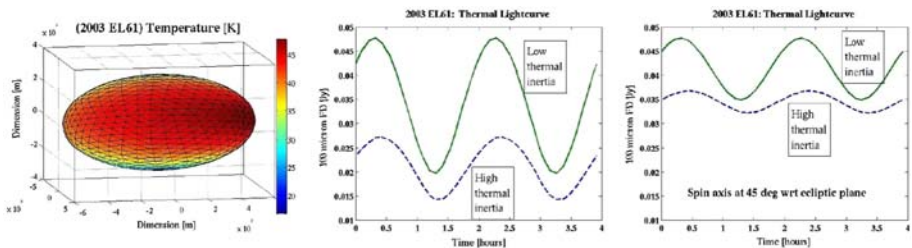

Fig. 3 *Left*: Thermophysical temperature calculation for 2003 EL_{61}, as seen from *Herschel*. Thermal properties are based on Spitzer data (Stansberry et al. 2008), the shape information was taken from Rabinowitz et al. (2006). Based on such a model, thermal lightcurves can be predicted and the influences of surface properties, spin vector orientation and wavelength can be studied. Corresponding thermal 100 μm lightcurves for 2003 EL_{61} are shown in the *middle* (spin vector perpendicular to the ecliptic plane) and *right* figure (spin axis at 45°)

Finally, we will constrain the thermophysical properties of our lightcurve targets (see paragraph D and Fig. 3 below).

Thermal inertia and surface emissivity results will be correlated with near-IR spectroscopic information on the surface composition. This study will also open the possibility of reliably interpreting current and future ground-based observations. Information about the

long wavelength emissivity is especially important in view of the potential of the Atacama Large Millimeter Array (ALMA), which will be able to detect TNOs with diameters below 100 km.

2.4 TNO Lightcurves: Shape or Albedo Effects?

About 50 TNOs exhibit measured lightcurves, i.e. repeatable variations of their visible magnitude with rotational phase. With the exception of Pluto, which is spherical and has a lightcurve due to albedo spots, and a few eclipsing contact binary candidates, these lightcurves are attributed to shape effects and the degree of elongation can be inferred from the amplitude of the lightcurves. However, possible albedo variations on the surface are usually not accounted for when interpreting lightcurves. This may influence the determination of the axis ratios and induces an ambiguity in the rotation period. Unlike in the case of albedo markings, the rotation period of an elongated object is twice the period of its lightcurve. This has important implications notably because constraints on the density can be derived from rotation periods and axis ratio, e.g. in the case of the bright objects 136,108 Haumea (Lacerda and Jewitt 2007) and Varuna (Jewitt and Sheppard 2002).

The ambiguity can be solved by observing thermal lightcurves (in this project we concentrate on six well-selected targets). The thermal lightcurve of an object whose visible lightcurve is primarily due to shape (albedo) will be correlated (anti-correlated) with the visible lightcurve. In addition, a thermal lightcurve may show a phase shift due to surface thermal inertia, which can therefore be measured. This has been done for Pluto (Lellouch et al. 2000). In the case of shape effects, the mean flux value and the amplitude of the thermal lightcurve are also diagnostic of the distribution of temperatures on the object, thereby constraining the spin vector and the thermal inertia (Fig. 3). Our thermophysical model predictions, combined with the experience from thermal lightcurve interpretations (e.g. thermophysical results for 25143 Itokawa by Müller et al. (2005) vs. in-situ results from the Hayabusa mission) demonstrate that the lightcurve studies provide solid constraints on thermophysical and surface parameters.

3 TNO Sample & Herschel Observations

Our *Herschel* programme includes a total of 137 TNOs, 25 of which are known binary or multiple systems, and 2 planetary satellites. Figure 4 shows the distribution of selected orbital parameters of our sample in comparison to the currently known TNOs.

For all these objects, we include PACS dual-band point-source photometry (70/160 and 100/160 μm at different observing times). Based on our model predictions we have grouped the TNOs in "weak" and "normal" targets and adjusted the integration times to reach S/N values of around 10 in all 3 bands. For the 15 brightest TNOs of our sample at 250 μm, we will perform additional SPIRE 3-band photometry, using the scan map mode, allowing a more detailed thermophysical characterisation of these targets. For six selected TNOs which have well-established visual lightcurves we plan repeated dual-band photometry with PACS (either 70/160 or 100/160 μm) to cover the full rotation period. Our target list also includes Saturn's satellite Phoebe, which is widely believed to be a captured Centaur (Johnson and Lunine 2005) Is has well-established physical properties (Simonelli et al. 1999; Porco et al. 2005; Flasar et al. 2005) from up-close studies by the Voyager 2 and Cassini spacecrafts. The Phoebe observations will mainly be used for validation purposes.
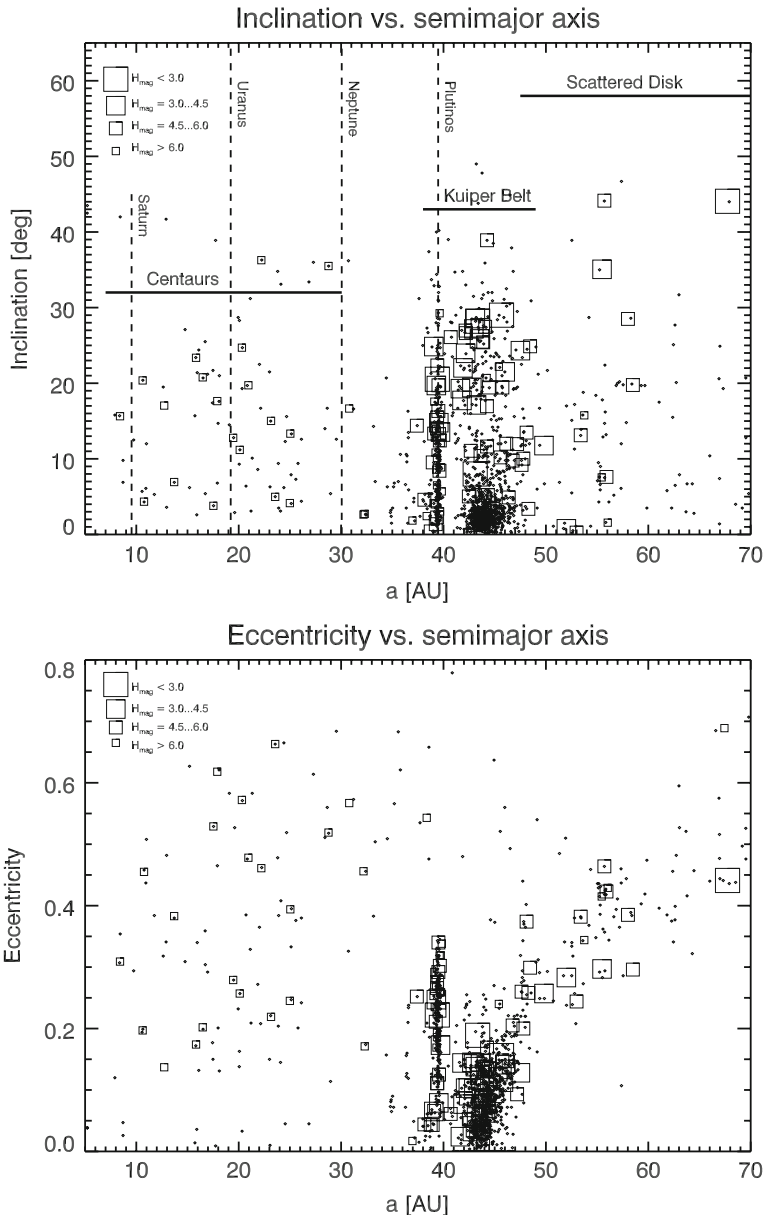
Inclination vs. semimajor axis

Eccentricity vs. semimajor axis

Fig. 4 Overview of our *Herschel* sample (*squares*) in comparison with the currently known Centaurs and TNOs (*dots*). *Top*: Inclination vs. semimajor axis. *Bottom*: Eccentricity vs. semimajor axis. The size of the *square-symbols* indicates the opposition H-magnitude, the regions of Centaurs, Kuiper Belt und Scattered Disk are indicated together with the semimajor axis of the outer planets

Our scientific analysis will start with the reduced and calibrated flux densities of the TNOs in this programme. First, the measured fluxes per target are the basis for deriving object-specific properties, like effective diameter and albedo, the temperature distribution across the objects, to investigate their thermal properties including thermal inertia,

Table 1 Summary of the Herschel Open Time Key Program "TNOs are cool"

	Sample	No.	Instrument/bands	Major science goals	Time (h)
A	Large sample[a]	114	PACS: all 3 bands	Albedo & sizes	239
B	Binary TNOs	25	PACS: all 3 bands	System albedo, size & density	56
C	Bright TNOs[b]	15	SPIRE: 3 bands	Detailed thermal studies	33
D	Selected TNOs[c]	6	PACS: 2 bands	Thermal lightcurve studies	44
					Total time = 372 h

[a] Including Phoebe and Sycorax

[b] Also part of the large sample (including Phoebe)

[c] Also part of the large sample

emissivity, surface roughness, making assumptions about their spin state. Time series of photometric measurements will be combined to produce thermal lightcurves. This will enable us to disentangle shape vs. albedo effects. The wavelength coverage from 70 to 500 μm will help to understand better the complete thermal emission of TNOs. For binary or multiple systems, the effective size and effective albedo will be derived. Combining the effective size with the system mass will provide the mean density of the system.

Second, we will establish the size and albedo distribution in the region beyond Neptune. The size distribution of these large bodies is thought to have survived unchanged from the growth epoch. Therefore, accurate measurement of the size distribution provides an unprecedented opportunity to determine the size spectrum produced by the accretional processes in the proto-planetary dust of the Sun.

Third, this catalogue of TNO albedo/sizes will be combined with the available colour and spectral information and with orbital parameters. Correlations between certain physical and dynamical properties of the TNO population as a whole and in subgroups will be searched for.

4 Groundbased Observational Support

Interpreting the thermal measurements in terms of the diameter and geometric albedo requires an accurate knowledge of the opposition V magnitude. This information is partially available or will be determined from our ground-based support programme. Some of our targets are regularly seen at various visible wavelengths by state-of-the-art survey programs. In addition, Pan STARRS will be operational starting in 2009. Nonetheless, we are performing additional ground-based observations whenever necessary. This is particularly true for thermal lightcurve studies, which require properly phased optical lightcurves. For the few targets in question, we will acquire new optical lightcurves close in time to the *Herschel* observations.

A few of our TNO targets have currently predicted position uncertainties that may not allow safe detection in the *Herschel* instrument field of view. This problem must be overcome by new astrometric measurements of the respective targets either through on-going or future TNO search and recovery observations around the world or through dedicated observations of the respective targets close in time to the *Herschel* measurements. "Uncertain" targets not recovered before *Herschel* observations will be replaced by other adequate and suitable objects with well-known orbits by the time of the observations.

One of our goals is to search for correlations between size, albedo and other physical parameters. It is believed that such correlations may indicate links to the objects' formation and/or pathway of their evolution. This task will be facilitated by existing TNO databases of visible/near-IR colours and spectra from two ESO Large Programs and recent work in literature. For targets which lack this information (some of the fainter targets) it is required to observe with large-aperture telescopes in parallel to this key programme.

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