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“TNOs are Cool”: A survey of the trans-Neptunian region

IV. Size/albedo characterization of 15 scattered disk and detached objects observed with *Herschel*-PACS^{★,★★}

P. Santos-Sanz¹, E. Lellouch¹, S. Fornasier^{1,2}, C. Kiss³, A. Pal³, T. G. Müller⁴, E. Vilenius⁴, J. Stansberry⁵, M. Mommert⁶, A. Delsanti^{1,7}, M. Mueller^{8,9}, N. Peixinho^{10,11}, F. Henry¹, J. L. Ortiz¹², A. Thirouin¹², S. Protopapa¹³, R. Duffard¹², N. Szalai³, T. Lim¹⁴, C. Ejeta¹⁵, P. Hartogh¹⁵, A. W. Harris⁶, and M. Rengel¹⁵

¹ LESIA-Observatoire de Paris, CNRS, UPMC Univ. Paris 6, Univ. Paris-Diderot, 5 place J. Janssen, 92195 Meudon Cedex, France
e-mail: pablo.santos@obspm.fr

² Univ. Paris Diderot, Sorbonne Paris Cité, 4 rue Elsa Morante, 75205 Paris, France

³ Konkoly Observatory of the Hungarian Academy of Sciences, Budapest, Hungary

⁴ Max-Planck-Institut für extraterrestrische Physik (MPE), Garching, Germany

⁵ University of Arizona, Tucson, USA

⁶ Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institute of Planetary Research, Berlin, Germany

⁷ Laboratoire d'Astrophysique de Marseille, CNRS & Université de Provence, Marseille, France

⁸ SRON LEA/HIFI ICC, Postbus 800, 9700 AV Groningen, The Netherlands

⁹ UNS-CNRS-Observatoire de la Côte d'Azur, Laboratoire Cassiopée, BP 4229, 06304 Nice Cedex 04, France

¹⁰ Center for Geophysics of the University of Coimbra, Av. Dr. Dias da Silva, 3000-134 Coimbra, Portugal

¹¹ Astronomical Observatory, University of Coimbra, Almas de Freire, 3040-004 Coimbra, Portugal

¹² Instituto de Astrofísica de Andalucía (CSIC), Granada, Spain

¹³ University of Maryland, USA

¹⁴ Space Science and Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

¹⁵ Max-Planck-Institut für Sonnensystemforschung (MPS), Katlenburg-Lindau, Germany

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ABSTRACT

Context. Physical characterization of trans-Neptunian objects, a primitive population of the outer solar system, may provide constraints on their formation and evolution.

Aims. The goal of this work is to characterize a set of 15 scattered disk (SDOs) and detached objects, in terms of their size, albedo, and thermal properties.

Methods. Thermal flux measurements obtained with the *Herschel*-PACS instrument at 70, 100 and 160 μm , and whenever applicable, with *Spitzer*-MIPS at 24 and 70 μm , are modeled with radiometric techniques, in order to derive the objects' individual size, albedo and when possible beaming factor. Error bars are obtained from a Monte-Carlo approach. We look for correlations between these and other physical and orbital parameters.

Results. Diameters obtained for our sample range from 100 to 2400 km, and the geometric albedos (in *V* band) vary from 3.8% to 84.5%. The unweighted mean *V* geometric albedo for the whole sample is 11.2% (excluding Eris); 6.9% for the SDOs, and 17.0% for the detached objects (excluding Eris). We obtain new bulk densities for three binary systems: Ceto/Phorcys, Typhon/Echidna and Eris/Dysnomia. Apart from correlations clearly due to observational bias, we find significant correlations between albedo and diameter (more reflective objects being bigger), and between albedo, diameter and perihelion distance (brighter and bigger objects having larger perihelia). We discuss possible explanations for these correlations.

Key words. Kuiper belt: general – infrared: planetary systems – methods: observational – techniques: photometric

1. Introduction

Since the detection of the first trans-Neptunian object (TNO) 20 years ago – 1992 QB₁ – (Jewitt & Luu 1992) besides Pluto, about 1550 TNOs/Centaurs have been discovered (as of October 2011). Different dynamical classes, according to their orbital parameters, have been identified within this distant icy population: classical objects with moderate eccentricity

orbits; resonant objects trapped in mean motion resonances with Neptune (Plutinos, in the 3:2 resonance with Neptune, represent the most populated resonant group, Jewitt & Luu 2000); scattered disk objects (SDOs) with high eccentricities and sometimes high inclinations, resulting from close encounters with Neptune; detached objects, whose perihelia are well outside Neptune's orbit (Gladman et al. 2002), and which likely constitute a large population in the outer Kuiper Belt; centaurs, which reside between the orbits of Jupiter and Neptune, represent TNOs scattered towards the inner solar system, and so are usually considered as Kuiper Belt objects (KBOs). Although it is convenient to classify objects by “populations”, the limits between some of these populations (i.e. between SDOs, centaurs,

* *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. PACS: The Photodetector Array Camera and Spectrometer is one of *Herschel*'s instruments.

** Appendices are available in electronic form at

<http://www.aanda.org>

high inclination/high eccentricity classicals, detached, etc.) are often “blurred” and may ultimately rely on definition (Gladman et al. 2008). The present paper deals with 15 SDO or detached objects, for which we first specify the adopted definition.

The terminology “scattered disk” was originally used for TNOs with orbits characterized by both a high eccentricity and a perihelion close to Neptune. It is believed that the majority of SDOs have unstable orbits due to close encounters with Neptune, but some of them could have survived since the origin of the solar system (Duncan & Levison 1997). Alternatively, the origin of the scattered disk could be related to other effects, including sweeping resonances that move the objects to this region (Malhotra 1995), passing star (or stars) (Morbidelli & Levison 2004, and references therein). Several approaches to the classification of objects as SDOs numerically integrate their orbits backward in time over dozens of millions of years (Elliot et al. 2005; Gladman et al. 2008). Here we adopt the Gladman et al. (2008) classification, which defines SDOs as those objects, independently of their origin, that are currently scattering actively off Neptune. SDOs are characterized by the rapid variation of semi-major axis in the orbit integrations. Specifically, Gladman et al. (2008) adopt a criterion similar to Morbidelli et al. (2004): the object is classified as an SDO if its semimajor-axis presents a variation ≥ 1.5 AU during a 10-m.y. backward integration. The exact value used (1–2 AU variation) makes little difference, as SDOs undergo large semimajor-axis changes in short times. Then, SDOs in this nomenclature might be called “scattering” objects instead of “scattered” objects. Following this classification SDOs exist over a large semi-major axis range, not only restricted to $a > 50$ AU; rather the SDO population extends down to the Centaur region (beginning at $a = 30$ AU). At the other edge the inner Oort cloud would begin at very large semimajor-axes ($a > 2000$ AU, Gladman et al. 2008).

Detached objects (Delsanti & Jewitt 2006) are also known as “extended scattered disk objects” (ESDOs), though it is preferable to use the term “detached” because not all these objects have necessarily been placed in this region through scattering. Detached objects have orbits with perihelion distances unaffected (“decoupled”) from the giant planets, in particular Neptune. This population may include inner Oort cloud bodies or transitional objects between SDOs and inner Oort cloud objects. The limits in parameter space are unknown, and are expanding with the new discoveries of TNOs at larger and larger semimajor axes – e.g. $a = 965$ AU for 2006 SQ₃₇₂ – (Gladman et al. 2002). Elliot et al. (2005) adopted the Tisserand parameter (T) relative to Neptune to define the detached population. A problem with this definition is the large number of high inclination TNOs within the classical population. In the Gladman et al. (2008) scheme, numerical integrations separate SDOs from detached TNOs. A remaining issue is to decide where the detached population ends towards low eccentricities; Gladman et al. (2008) adopt a lower bound of $e = 0.24$. Possible processes that placed the detached objects on these orbits are currently being investigated (e.g. Gomes et al. 2008; Kenyon et al. 2008; Duncan et al. 2008, etc.).

Determining KBO sizes and albedos is not a straightforward task. Measurements from direct imaging are available for only a handful of them (Brown & Trujillo 2004; Brown et al. 2006). Most recently, sizes have become available from stellar occultations (Elliot et al. 2010; Sicardy et al. 2011). Obtaining size/albedo values for a larger sample is best achieved from thermal radiometry, whereby thermal and optical observations are combined within a thermal model. After the pioneering measurements on two objects from ISO (Thomas et al. 2000)

and ground-based observations on a few others (see Stansberry et al. 2008, and references therein), *Spitzer* provided the first large such dataset, with about 60 Centaurs/KBOs measured at 24 and/or 70 μm (Cruikshank et al. 2005; Grundy et al. 2005, 2007; Stansberry et al. 2006, 2008; Brucker et al. 2009). This approach (multi-wavelength photometry) also constrains the thermal regime of the object, phenomenologically described by the “beaming factor” (Jones & Morrison 1974; Lebofsky & Spencer 1989; Harris 1998). The launch of *Herschel* Space Observatory in 2009 offered a new tool for this purpose, providing photometry over 6 bands from 70–500 μm . Early results on a handful of objects were presented in Müller et al. (2010), Lim et al. (2010), and Lellouch et al. (2010). Beyond their intrinsic scientific value, albedos are needed to properly interpret reflectance spectra. Furthermore, correlations between size, albedo, color, composition and orbital parameters may provide diagnostics on the dynamical, collisional and physical history of KBOs. The size distribution of TNOs is also a diagnostic relating to that history, but in the absence of measured sizes the distribution has typically been estimated from the luminosity function and an assumed albedo, an uncertain step given that the average albedos seem to be different for the different dynamical populations (Grundy et al. 2005; Brucker et al. 2009). Instead, and to constrain Kuiper belt formation/evolution models it is desirable to directly determine the size distribution of the different populations, and infer their individual total masses. Large bodies retain information about the angular momentum of the presolar nebula and their size distribution is dominated by accretion. On the other hand, small bodies – in the 50 to 100 km range – are the result of collisional evolution (Petit et al. 2008).

A large program (370 h of telescope time), named “TNOs are Cool: A survey of the trans-Neptunian region” (Müller et al. 2009), has been awarded on *Herschel* to measure the thermal flux of about 140 KBOs/Centaurs. We present here results on 15 SDO and detached objects. These observations lead to new sizes/albedos for 9 objects and improved results on 6 others. Results on 19 classical and 18 Plutinos are presented in companion papers by Vilenius et al. (2012) and Mommert et al. (2012), respectively.

2. Observations

The *Herschel* Space Observatory (Pilbratt et al. 2010) is a 3.5 m telescope launched on 14 May 2009, covering the far-infrared range by means of three focal plane instruments. The “TNOs are Cool” program consists of photometry of ~ 140 objects, mostly with the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010).

The PACS instrument has 3 photometric bands centered at 70, 100 and 160 μm . These bands (termed “blue”, “green” and “red”, respectively) cover the 60–85 μm , 85–130 μm , 130–210 μm ranges. With two bolometer arrays, PACS can observe a field in two bands at a time: blue/red or green/red. The red detector is a 32×16 pixel array, while the blue/green is 64×32 pixels. The 3 bands image the same field of view of $3.50' \times 1.75'$. Projected onto the sky, pixel sizes are $6.4'' \times 6.4''$ (red band) and $3.2'' \times 3.2''$ (blue/green bands), respectively.

The observations discussed here were performed using the scan map mode. This mode was selected due to its better overall performance compared to the point-source (chop-nod) mode (Müller et al. 2010). Scan maps are performed by slewing the spacecraft at a constant speed along parallel lines, or “legs”. Our observations were typically performed at medium speed (20''/s). We use 10 scan legs in each map, separated by 4''. The length

Table 1. Orbital parameters, absolute magnitudes, $B - R$ colors, photometric variation, taxonomy, dynamical classification, and multiplicity of the observed objects.

Object	a [AU]	q [AU]	i [deg]	e	H_V [mag]	$B - R$ [mag]	P [h]	Δm_R [mag]	Taxon.	Class.
1996 TL ₆₆	84.5	35.0	23.9	0.59	$5.39 \pm 0.12^{a,b,c}$	$1.11 \pm 0.07^{c,q,r,s}$	12.0 ^x	$<0.12, <0.06^{x,y}$	BB	SDO
2001 FP ₁₈₅	212.0	34.3	30.8	0.84	$6.39 \pm 0.07^{a,b}$	$1.40 \pm 0.06^{b,t}$	...	$<0.06^z$	IR	SDO
2002 PN ₃₄	31.2	13.4	16.6	0.57	$8.66 \pm 0.03^{a,d}$	1.28 ± 0.02^f	8.45/10.22 ^α	0.18 ± 0.04^{α}	BB-BR	SDO
2002 XU ₉₃	66.5	21.0	77.9	0.69	$8.11 \pm 0.10^{e,f}$	1.20 ± 0.02^e	...	...	...	SDO
2007 OR ₁₀	67.1	33.6	30.7	0.50	1.96 ± 0.16^g	...	...	...	...	SDO
2007 RW ₁₀	30.4	21.2	36.0	0.30	6.39 ± 0.61^g	...	...	...	...	SDO
(2003 FX ₁₂₈) Ceto* ^δ	99.7	17.8	22.3	0.82	$6.54 \pm 0.06^{h,i}$	1.42 ± 0.04^f	4.43 ⁿ	0.13 ± 0.02^n	...	SDO
(2002 CR ₄₆) Typhon* ^j	37.6	17.5	2.4	0.54	$7.72 \pm 0.04^{a,d,f,h,j,k,m}$	$1.29 \pm 0.07^{m,t}$	9.67/19.34 ^{y,α}	$0.06 \pm 0.01^{y,α}$	BR	SDO
1999 KR ₁₆	48.7	33.9	24.9	0.30	$5.37 \pm 0.08^{n,o}$	$1.87 \pm 0.07^{c,u,v}$	5.93/11.86 ⁿ	0.18 ± 0.04^n	RR	DO
2003 FY ₁₂₈	49.2	37.0	11.8	0.25	5.09 ± 0.09^k	1.65 ± 0.02^e	8.54 ^y	0.15 ± 0.01^y	BR	DO
2005 QU ₁₈₂	114.0	37.0	14.0	0.68	3.80 ± 0.32^f	...	...	...	...	DO
2005 TB ₁₉₀	76.5	46.2	26.4	0.40	4.40 ± 0.11^f	1.54 ± 0.03^e	...	...	...	DO
2007 OC ₁₀	50.0	35.5	21.7	0.29	$5.43 \pm 0.10^{f,i}$	...	...	...	...	DO
2007 UK ₁₂₆ * ^ζ	74.0	37.7	23.4	0.49	3.69 ± 0.10^k	...	...	...	...	DO
(2003 UB ₃₁₃) Eris* ^ε	68.1	38.6	43.8	0.43	$-1.12 \pm 0.03^{d,p}$	$1.21 \pm 0.09^{d,w}$	13.69/28.08 ^β 32.13/25.92 ^{β,γ}	$<0.1, 0.01^{β,γ}$	BB	DO

Notes. * Indicates that the object is a known binary/multiple system. H_V [mag]: average visual magnitude obtained from papers referenced below. Numbers in bold indicate H_R magnitudes instead of H_V . See text for details about the absolute magnitude estimation. $B - R$ [mag] colors (when available). P [h] single or double-peaked rotational period. Δm_R [mag]: lightcurve amplitude. Taxon.: taxonomic color class (Perna et al. 2010, and references therein). Class.: dynamical classification following Gladman et al. (2008). SDO = scattered disc object, DO = detached object.

References. ^(a) Romanishin & Tegler (2005); ^(b) Doressoundiram et al. (2005); ^(c) Jewitt & Luu (2001); ^(d) Rabinowitz et al. (2007); ^(e) Sheppard (2010); ^(f) Derived from MPC V-data; ^(g) Derived from MPC R-data; ^(h) Benecchi et al. (2009); ⁽ⁱ⁾ Perna & Dotto (2011, priv. comm.); ^(j) Grundy et al. (2008); ^(k) Perna et al. (2010); ^(m) Peixinho et al. (2004); ⁽ⁿ⁾ Sheppard & Jewitt (2002); ^(o) Belskaya et al. (2003); ^(p) Sheppard (2007); ^(q) Tegler & Romanishin (1998); ^(r) Jewitt & Luu (1998); ^(s) Barucci et al. (1999); ^(t) Tegler et al. (2003); ^(u) Trujillo & Brown (2002); ^(v) Boehnhardt et al. (2002); ^(w) Tegler (2011, priv. comm.); ^(x) Ortiz et al. (2006); ^(y) Thirouin et al. (2010); ^(z) Sheppard & Jewitt (2003); ^(α) Ortiz et al. (2003); ^(β) Duffard et al. (2008); ^(γ) Roe et al. (2008); ^(δ) Grundy et al. (2007); ^(ε) Brown & Schaller (2007); ^(ζ) Noll et al. (2009).

of each leg is 3.0'. Each such scan-map is repeated two to five times, depending on the expected brightness of the objects (see below). Within a single scan map, either the blue-red or the green-red channel combination is selected. For any band selection, two individual maps are made using two scanning directions with respect to the detector array: 70° and 110°, allowing to fit the scan pattern on the rectangular array in an optimum way.

The “TNOs are cool” target list was constructed by predicting the thermal fluxes in the PACS bands for the known TNOs using the “hybrid standard thermal model” (STM – see Sect. 4). The flux predictions were based on absolute visual magnitudes (H) from the Minor Planet Center (MPC), an assumed visual geometric albedo of 8% (based on previous studies using *Spitzer*), and geometric circumstances appropriate to the expected observing epoch (c. 2010). For objects with known albedos (for this study those were Eris: 70%, Typhon: 5%, 1996 TL₆₆: 4%, and 2002 PN₃₄: 5%) we used those values rather than the 8% assumption. Objects with the largest predicted thermal fluxes were selected as potential targets; that list was further refined by rejecting objects with predicted positional uncertainties $<5''$. The objects presented in this paper are a subset of the targets selected in the above manner. Once the targets were selected, integration times were chosen to provide signal-to-noise ratio (SNR) values of ~ 10 in the blue and green channels. Integration times for individual observations were tailored by varying the repetition factor for the scan maps described earlier. Note that the values of H from the MPC were used for planning purposes only, and can differ significantly (by up to 0.5 mag) from the values ultimately used in our analysis.

It is important to note that the target selection process introduces a bias towards brighter (low H values) objects. A consequence of the assumed and generally fixed albedo is that

the object sample favors large objects at large heliocentric distances (r_h). In addition, the object sample is affected by a discovery bias that: (i) favors high-albedo objects at high r_h , and (ii) introduces a correlation between the perihelion (q) and the heliocentric distance, because objects are most easily discovered near perihelion and haven’t moved much since discovery. These biases and correlations must be kept in mind when studying correlations between size, albedo and other physical and orbital parameters (see Sect. 5). As for the present SDOs/Detached sample, objects are listed in Table 1, including relevant orbital parameters, absolute magnitudes in V -band, rotational periods and amplitudes, taxonomic color class (when known), existence or not of satellites, and dynamical classification following Gladman et al. (2008). Observational circumstances are described in more details in Table 2.

Each target was visited twice, with identical observations repeated in both visits. During the first visit, we grouped 4 maps to be observed in sequence, corresponding to the two scan directions and the two channel combinations. The observation geometry is such that on the final combined map, the central $\sim 50'' \times 50''$ region has high coverage. Photometric accuracy is usually limited by instrumental noise in the blue channel and by background confusion noise in the red, while either of the two sources of noise may dominate in the green¹. The timing of the observations, i.e. the selection of the visibility window, was optimized to ensure the lowest far-infrared confusion noise circumstances (Kiss et al. 2005), in such a way that the estimated SNR due to confusion noise has its maximum in the green channel.

¹ PACS AOT Release Note: PACS Photometer Point/Compact Source Mode, 2010, PICS-ME-TN-036, Version 2.0, custodian T. Müller, <http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb>

Table 2. Individual observational circumstances.

Object	OBSIDs	Dur. [min]	Mid-time	r_h [AU]	Δ [AU]	α [deg]
(15874) 1996 TL ₆₆	1342190953-0956	39.7	22-Feb.-2010 10:57:34	35.7245	35.8103	1.59
(15874) 1996 TL ₆₆	1342191029-1032	39.7	23-Feb.-2010 12:09:47	35.7250	35.8289	1.59
(82158) 2001 FP ₁₈₅	1342211422-1425	97.4	23-Dec.-2010 08:41:10	34.9353	35.2646	1.53
(82158) 2001 FP ₁₈₅	1342211528-1531	97.4	23-Dec.-2009 21:36:49	34.9356	35.2562	1.53
(73480) 2002 PN ₃₄	1342213067-3070	41.0	18-Jan.-2011 14:18:48	17.5092	17.8769	2.99
(73480) 2002 PN ₃₄	1342213089-3092	41.0	18-Jan.-2011 21:31:02	17.5098	17.8821	2.98
(127546) 2002 XU ₉₃	1342204211-4214	59.8	09-Sep.-2010 14:56:03	21.1063	21.4432	2.58
(127546) 2002 XU ₉₃	1342204240-4243	59.8	09-Sep.-2010 21:19:45	21.1064	21.4399	2.58
2007 OR ₁₀	1342220081-0084	78.6	07-May-2011 02:16:22	86.3285	86.5992	0.65
2007 OR ₁₀	1342220272-0275	78.6	09-May-2011 23:59:21	86.3305	86.5534	0.66
2007 RW ₁₀	1342213219-3222	59.8	24-Jan.-2010 05:43:55	27.4552	27.8385	1.90
2007 RW ₁₀	1342213270-3273	59.8	24-Jan.-2011 21:05:07	27.4558	27.8495	1.89
(65489) Ceto	1342202877-2880	59.8	11-Aug.-2010 20:15:24	31.6508	31.8552	1.81
(65489) Ceto	1342202910-2913	59.8	12-Aug.-2010 11:00:59	31.6524	31.8666	1.80
(42355) Typhon	1342210596-0599	59.8	30-Nov.-2010 21:13:47	18.2160	18.5731	2.90
(42355) Typhon	1342210624-0627	59.8	01-Dec.-2010 03:50:07	18.2162	18.5690	2.91
(40314) 1999 KR ₁₆	1342212814-2817	97.4	17-Jan.-2011 20:35:59	35.7593	36.0633	1.51
(40314) 1999 KR ₁₆	1342213071-3074	97.4	18-Jan.-2011 15:51:40	35.7589	36.0497	1.51
(120132) 2003 FY ₁₂₈	1342212770-2773	59.8	16-Jan.-2011 19:01:01	38.8406	38.6763	1.45
(120132) 2003 FY ₁₂₈	1342213107-3110	59.8	19-Jan.-2011 05:03:50	38.8416	38.6356	1.44
2005 QU ₁₈₂	1342212619-2622	41.0	14-Jan.-2011 14:46:12	48.8994	49.1349	1.13
2005 QU ₁₈₂	1342212696-2699	41.0	15-Jan.-2011 14:01:49	48.9008	49.1522	1.12
(145480) 2005 TB ₁₉₀	1342221729-1732	78.6	27-May-2011 03:17:15	46.3134	46.5135	1.24
(145480) 2005 TB ₁₉₀	1342221782-1785	78.6	28-May-2011 13:15:54	46.3132	46.4900	1.25
2007 OC ₁₀	1342206671-6674	59.8	16-Oct.-2010 21:52:04	35.5187	35.1842	1.54
2007 OC ₁₀	1342206698-6701	59.8	18-Oct.-2010 11:48:52	35.5189	35.2090	1.55
(229762) 2007 UK ₁₂₆	1342202277-2280	41.0	08-Aug.-2010 18:09:36	44.9448	45.1702	1.27
(229762) 2007 UK ₁₂₆	1342202324-2327	41.0	09-Aug.-2010 13:05:14	44.9440	45.1572	1.27
(136199) Eris	1342199487-9490	59.8	30-Jun.-2010 21:01:08	96.6522	96.8807	0.59
(136199) Eris	1342199753-9756	59.8	03-Jul.-2010 19:45:58	96.6518	96.8326	0.60

Notes. OBSIDs: *Herschel* internal observation IDs. Dur. [min]: total duration of the 4 OBSIDs observations for the red band. For the blue and green channels the time is half of this value. Mid-time: mean date and UT time of the observation. r_h [AU]: heliocentric distance (AU) at mid-time. Δ [AU]: distance object-*Herschel* (AU) at mid-time. α [deg]: phase angle -degrees- at mid-time.

The timing of the second visit was calculated such that the target moved 30–50'' between the two visits. This ensures that the target position during the second visit is still within the high-coverage area of the map from the first visit. At the same time, this enables us to determine and subtract the background in the individual maps, so as to obtain a clean combined image where we extract the final flux (see Sect. 3.1).

3. Data reduction and photometry

In this section, we first describe the reduction process applied to the PACS data in order to obtain what we call “single” and “combined” maps, and then the photometric techniques used to determine the target fluxes and associated uncertainties in each band. Further details of the data reduction are given in Appendix A.

3.1. Data reduction

The data reduction of the PACS maps was performed within the *Herschel* interactive processing environment (HIPE², version 6.0.2044) by means of adapted standard HIPE scripts. Since our targets move slowly (a few ''/h), and the total observation time per scanning direction in one visit is only 10–25 min, we do not correct for the apparent motion.

After the application of the HIPE scripts we obtain one “single” map per visit, filter, and scan direction (i.e. in total 8 maps

per object in the red, and 4 maps in the blue/green). The final re-sampled pixel scale of the single maps are 1.1''/pixel, 1.4''/pixel, and 2.1''/pixel for the blue (70 μm), green (100 μm) and red (160 μm) channels respectively.

We use these single maps to generate final “combined” maps on which the photometry will be performed. To generate the combined maps, we combine the two visits to the target to determine the background map and subtract it from each single map. Finally we co-add all the background-subtracted maps in the co-moving frame of the target. Similar methods were used to subtract background sources in *Spitzer* TNO observations, and are described in Stansberry et al. (2008) and Brucker et al. (2009). An alternate, simpler method, to obtain final maps is to co-add directly the original single maps (i.e. not background-corrected) in the target frame. This method is obviously less optimal than the previous one in terms of SNR, but provides a useful test to demonstrate that the background subtraction is not introducing any spurious effects. A more complete and detailed description about the data reduction process can be found in Appendix A, and will be published in Kiss et al. (in prep.-a).

3.2. Photometry

We use IRAF/Daophot³ to perform standard synthetic-aperture photometry on the final sky-subtracted, co-added maps for our

² HIPE is a joint development by the *Herschel* Science Ground Segment Consortium, consisting of ESA, the NASA *Herschel* Science Center, and the HIFI, PACS and SPIRE consortia members, see: <http://herschel.esac.esa.int/DpHiPeContributors.shtml>

³ Image Reduction and Analysis Facility (IRAF), is a collection of software written at the National Optical Astronomy Observatory (NOAO) geared towards the reduction of astronomical images in pixel array form.

targets. The target is typically obvious and located very near the center of the maps. For very faint targets and/or ones with some residual structure from the background subtraction (as can happen in the green and red channels), the ephemeris position of the target is used to position the photometric aperture.

Once the target is identified, we measure the flux at the photometer position for aperture radii ranging from 1 to 15 pixels. We perform an aperture correction technique (Howell 1989) for each aperture radius using the encircled energy fraction for a point–source for the PACS instrument⁴. We construct an aperture-corrected curve-of-growth using these fluxes (red line of Fig. A.4). Given the optimized reduction technique above, the fluxes used to construct these aperture-corrected curves-of-growth need not be corrected for background contribution.

After inspection of the curves-of-growth, the optimum synthetic aperture to measure the target flux is selected, and is typically ~ 1.0 – 1.25 times the point spread function (PSF) full width at half maximum (FWHM) in radius (PSF FWHM in radius is $5.2''/7.7''/12''$ in blue/green/red bands respectively). Usually, the optimum aperture radius lies in the “plateau” zone of the curves-of-growth (see Fig. A.4). In cases in which there are other sources or artifacts very close to the target, we use a smaller aperture radius to avoid contamination of the target flux.

Uncertainties on the flux measurements are estimated by means of a Monte-Carlo technique, in which 200 artificial sources are implanted on the actual background-subtracted final maps. These artificial sources have the structure of the PSF for the specific (blue, green, or red) channel. Sources are randomly implanted on a square region of $50'' \times 50''$ around the target photometer, with an exclusion zone corresponding to a circular region around the target photometer with a radius $= 2 \times \text{PSF FWHM}$. We measure and aperture-correct the fluxes of these artificial sources using an aperture radius of 5 re-sampled pixels, which is the median optimum aperture radius. Uncertainties are computed as the standard deviation of these 200 fluxes, and finally multiplied by a factor $\sqrt{2}$. The latter factor is due to the fact that given the way the final maps are generated, the remaining background is measured only once in the immediate vicinity of the real target but two times in the rest of the image (i.e. for the artificial sources). Note that except for the background subtraction, all the above reduction and photometric steps were validated on standard stars with known flux.

The fluxes and associated uncertainties are finally color-corrected for each band. Flux densities within the PACS photometric system are defined as those that a source with a flat spectrum would have at the PACS reference wavelengths of 70, 100 and $160 \mu\text{m}$ (Poglitsch et al. 2010). Converting the in-band flux to monochromatic flux densities therefore depends on the spectral energy distribution of the source and the transmission profile for each PACS band. Color-corrections for each filter are tabulated as a function of color temperature⁵ but are usually within a few percent except at the very low end ($T < 30 \text{ K}$) of the temperature range. For the color temperature, we used an approximation of the disk-averaged temperature, i.e. $T_{\text{color}} = T_{\text{ss}}/2^{1/4}$, where T_{ss} , the subsolar temperature (see Eq. (2)), was

⁴ Müller et al. (2011): PACS Photometer – Point-Source Flux Calibration, PACC-ME-TN-037, Version 1.0; Retrieved November 23, 2011; http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/pacs_bolo_fluxcal_report_v1.pdf

⁵ Müller et al. (2011), PACS Photometer Passbands and Colour Correction Factors for Various Source SEDs, PACC-ME-TN-038, Version 1.0; Retrieved November 23, 2011; http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/cc_report_v1.pdf

Table 3. Color corrected fluxes at 70, 100 and $160 \mu\text{m}$ for the SDOs/Detached sample.

Object	Flux ₇₀ [mJy]	Flux ₁₀₀ [mJy]	Flux ₁₆₀ [mJy]	Class.
(15874) 1996 TL ₆₆	9.6 ± 1.2	9.7 ± 1.1	9.2 ± 2.2	SDO
(82158) 2001 FP ₁₈₅	9.2 ± 0.8	11.1 ± 1.1	7.0 ± 1.9	SDO
(73480) 2002 PN ₃₄	11.4 ± 1.2	11.9 ± 1.4	7.6 ± 6.1	SDO
(127546) 2002 XU ₉₃	16.5 ± 0.9	15.0 ± 1.6	6.2 ± 2.1	SDO
2007 OR ₁₀	3.7 ± 1.1	4.8 ± 1.4	6.7 ± 2.3	SDO
2007 RW ₁₀	13.2 ± 0.9	11.3 ± 1.3	10.3 ± 2.1	SDO
(65489) Ceto	12.3 ± 0.7	10.5 ± 1.0	6.2 ± 4.8	SDO
(42355) Typhon	28.5 ± 1.2	21.4 ± 1.2	9.1 ± 2.4	SDO
(40314) 1999 KR ₁₆	5.7 ± 0.7	3.5 ± 1.0	4.6 ± 2.2	DO
(120132) 2003 FY ₁₂₈	14.4 ± 0.9	14.0 ± 1.2	13.0 ± 2.2	DO
2005 QU ₁₈₂	4.5 ± 0.9	2.5 ± 1.1	8.4 ± 3.0	DO
(145480) 2005 TB ₁₉₀	5.8 ± 0.9	8.6 ± 1.4	5.4 ± 1.8	DO
2007 OC ₁₀	8.3 ± 0.9	7.8 ± 1.2	7.4 ± 1.8	DO
(229762) 2007 UK ₁₂₆	13.7 ± 1.1	12.3 ± 1.3	7.2 ± 2.2	DO
(136199) Eris	2.0 ± 0.6	3.7 ± 1.0	5.6 ± 1.6	DO

Notes. Flux₇₀, Flux₁₀₀, Flux₁₆₀: Color-corrected fluxes (mJy) at 70, 100 and $160 \mu\text{m}$. Class., dynamical classification following Gladman et al. (2008). SDO = scattered disc object, DO = detached object.

obtained from a first run of the thermal model described below, using at this step the in-band (i.e. color-uncorrected) fluxes. T_{color} values for our sample range from 25 K for Eris to 77 K for 2002 PN₃₄. The mean color correction factors for all our sample are: 0.991 ± 0.028 (blue band), 0.989 ± 0.006 (green band), and 1.011 ± 0.017 (red band). The impact of these factors is smaller than the uncertainties of our measurements.

The absolute flux calibration of PACS is based on standard stars and large main belt asteroids and has uncertainties of 3% for the blue/green channel, and 5% for the red channel⁶. The final flux uncertainties we use in our modeling are the root-sum-square combination of these absolute calibration uncertainties and the uncertainties we obtain from the photometric measurements for individual targets. A summary of the final, color-corrected and absolute-calibrated, fluxes of our SDOs/Detached sample is given in Table 3.

3.3. Spitzer-MIPS observations

About 102 TNOs/Centaurs have been observed with the 0.85 m *Spitzer* Space Telescope (Werner et al. 2004) using the Multiband Imaging Photometer (MIPS) instrument (Rieke et al. 2004). The MIPS $24 \mu\text{m}$ channel consist of a 128×128 pixel detector and the $70 \mu\text{m}$ channel of a 32×32 pixel detector. For these 2 channels the telescope-limited resolution is $6''$ and $18''$ respectively. Fluxes for 60 objects have been published in Stansberry et al. (2008) and Brucker et al. (2009) but others are unpublished. Eight targets of our sample have available (published or unpublished) *Spitzer*-MIPS flux density measurements at 24 and/or at $70 \mu\text{m}$ (see Table 4). Unpublished data have been processed in a similar way as in Stansberry et al. (2008) and Brucker et al. (2009), using the calibration (Gordon et al. 2007; Engelbracht et al. 2007) and color-corrections (Stansberry et al. 2007) described in the references. As in Stansberry et al. (2008), we adopt absolute calibration uncertainties of 3% and 6% for the 24 and $70 \mu\text{m}$ observations (50% larger than the uncertainties derived

⁶ Müller et al. (2011): PACS Photometer – Point-Source Flux Calibration, PACC-ME-TN-037, Version 1.0; Retrieved November 23, 2011; http://herschel.esac.esa.int/twiki/pub/Public/PacsCalibrationWeb/pacs_bolo_fluxcal_report_v1.pdf

Table 4. *Spitzer*-MIPS color corrected fluxes at 23.68 and 71.42 μm available for our SDOs/detached sample.

Object	Mid-time	r_h [AU]	Δ [AU]	α [deg]	Flux ₂₄ [mJy]	Flux ₇₀ [mJy]
(15874) 1996 TL ₆₆	2008-Feb.-17 04:27:11	35.4370	34.9378	1.4	0.324 ± 0.020^2	10.12 ± 1.40^2
(82158) 2001 FP ₁₈₅	2004-Jun.-20 22:51:52	34.2594	34.0927	1.7	0.395 ± 0.096^3	Contaminated flux
(73480) 2002 PN ₃₄	2006-Jul.-16 11:00:56	14.6074	14.1524	3.6	10.144 ± 0.117^2	30.34 ± 1.59^2
(127546) 2002 XU ₉₃	2006-Nov.-04 20:09:23	21.0896	20.8251	2.7	2.431 ± 0.052^3	14.12 ± 1.19^3
(65489) Ceto	2006-Jul.-19 03:19:41	27.9924	27.6753	2.0	1.419 ± 0.047^2	14.6 ± 2.6^1
(42355) Typhon	2008-Jun.-26 22:18:45	17.6784	17.5110	3.3	4.974 ± 0.125^3	27.46 ± 3.43^2
(120132) 2003 FY ₁₂₈	2007-Jul.-14 07:30:00	38.3556	38.1281	1.5	0.427 ± 0.051^3	19.38 ± 3.16^3
(136199) Eris	2005-Aug.-24 22:13:07	96.9049	96.4083	0.5	$<0.005^1$	2.7 ± 0.7^1

Notes. Mid-time: mean date and UT time of the observation. r_h [AU]: heliocentric distance (AU) for the observation date. Δ [AU]: distance object-*Spitzer* (AU) for this date. α [deg]: phase angle–degrees. Flux₂₄, Flux₇₀: *Spitzer*-MIPS color-corrected flux densities (mJy) at 23.68 μm and 71.42 μm . Upper limits are 1σ .

References. ⁽¹⁾ Stansberry et al. (2008); ⁽²⁾ Revised data from Stansberry et al. (2008); ⁽³⁾ previously unpublished data.

for observations of stellar calibrators). The larger uncertainties allow for effects from the background-subtraction technique, the faintness of the targets, and uncertainties in the color corrections. The background subtraction techniques used for our *Herschel* data (see Sect. 3.1) are in fact derived from techniques originally developed for the MIPS data reductions. The previously unpublished fluxes presented here are based on new reductions of the MIPS data, utilizing updated ephemeris positions for the targets. This allows for more precise masking of the target when generating the image of the sky background, and for more precise placement of the photometric aperture. In most cases the new fluxes are very similar to the previously published values for any given target, but in a few cases significant improvements in the measured flux and SNR were achieved.

As discussed below, the combination of *Spitzer*-MIPS and *Herschel*-PACS fluxes significantly improves results from the thermal modeling. The *Spitzer* 70 μm band is similar to the *Herschel* 70 μm channel, providing a consistency check on data from the two observatories. The inclusion of the *Spitzer* 24 μm flux, when available, strongly improves the ability to constrain the surface temperature distribution, i.e. in general, allows us to determine the beaming factor (see Sect. 4). Published, re-analyzed, and unpublished *Spitzer*-MIPS flux density measurements available for our sample are given in Table 4. Note that the effective wavelengths for these fluxes are 23.68 and 71.42 μm .

4. Thermal model

4.1. General formulation

The combination of thermal-infrared and optical data makes it possible to infer an objects' diameter (D), geometric albedo (p_V) and constrain its thermal properties. This requires the use of a thermal model to calculate the disk-integrated thermal emission. Here we use the so-called hybrid standard thermal model (hybrid STM, Müller et al. 2010; Stansberry et al. 2008). Except for the fact that the hybrid STM assumes zero phase angle (which is an excellent approximation for TNOs), it is identical to the Near-Earth Asteroid Thermal Model (NEATM, Harris 1998). NEATM was originally developed for Near Earth Objects (NEOs) but is applicable to all atmosphereless bodies and is being used in companion papers by Mommert et al. (2012) and Vilenius et al. (2012). In this model, the temperature distribution follows instantaneous equilibrium of a smooth spherical surface with solar input, but is modified by a factor η (beaming factor), which represents empirically the combined effects of thermal inertia and surface roughness. As shown by Harris (1998) and Stansberry et al. (2008), multi-wavelength measurements can be used to

constrain η if the data are of sufficient quality and encompass both the short-wavelength and the peak and/or long-wavelength portions of the spectral energy distribution (SED) of the target. In this case the data give a direct measurement of the color-temperature of the emission, which is sensitive to the value of η . Our preferred approach was to simultaneously model *Herschel* and *Spitzer* measurements (of course accounting for their different observer-centric, Δ , and heliocentric, r_h , distances) and fit an η factor to the combined dataset. We call this the “floating- η ” approach. When *Spitzer* data were unavailable (or when this method led to implausible η values; see Mommert et al. 2012) we instead used a “fixed- η ” approach, with $\eta = 1.20 \pm 0.35$, the mean value derived by Stansberry et al. (2008) from *Spitzer* observations of TNOs.

The model therefore fits the *Herschel* (3 data points) or *Herschel* + *Spitzer* (5 data points) fluxes in terms of two (D and p_V) or three (D , p_V , and η) parameters. The model also requires the choice on a phase integral q , that we assumed to be related to p_V through $q = 0.336p_V + 0.479$ (Brucker et al. 2009). Diameter and geometric albedo are further related through:

$$D = 2 \times 10^{V_\odot/5} \cdot 10^{-H/5} / \sqrt{p_V} \cdot 1 \text{ AU/km} \quad (1)$$

where H is the absolute magnitude (nominally in V band), and $V_\odot = -26.76 \pm 0.02$ (Bessell et al. 1998) the V magnitude of the Sun. A grey emissivity ($\epsilon = 0.9$) was assumed when calculating the local temperatures and monochromatic fluxes. With these definitions the subsolar temperature is given by:

$$T_{ss} = \left(\frac{F_\odot(1 - p_V q)}{r_h^2 \eta \epsilon} \right)^{1/4} \quad (2)$$

where F_\odot is the solar flux at 1 AU. The solution for the D , p_V (and η) parameters are determined from a χ^2 minimization of the deviation of the model from the observed fluxes, accounting for their individual $1-\sigma$ error bars. Note that when only upper limits were available, they were treated as non-detections (i.e. zero flux) with a $1-\sigma$ uncertainty as the upper limit. In the case of multiple systems D is the area-equivalent diameter, i.e., that of the sphere with the same total surface area, because none of the binaries are resolved in our data.

4.2. H magnitudes

Equation (1) above outlines the role of absolute magnitude (H) in the thermal modeling. Determining accurate values of H , preferably in V band, is therefore an essential task for this project. We describe hereafter our adopted approaches.

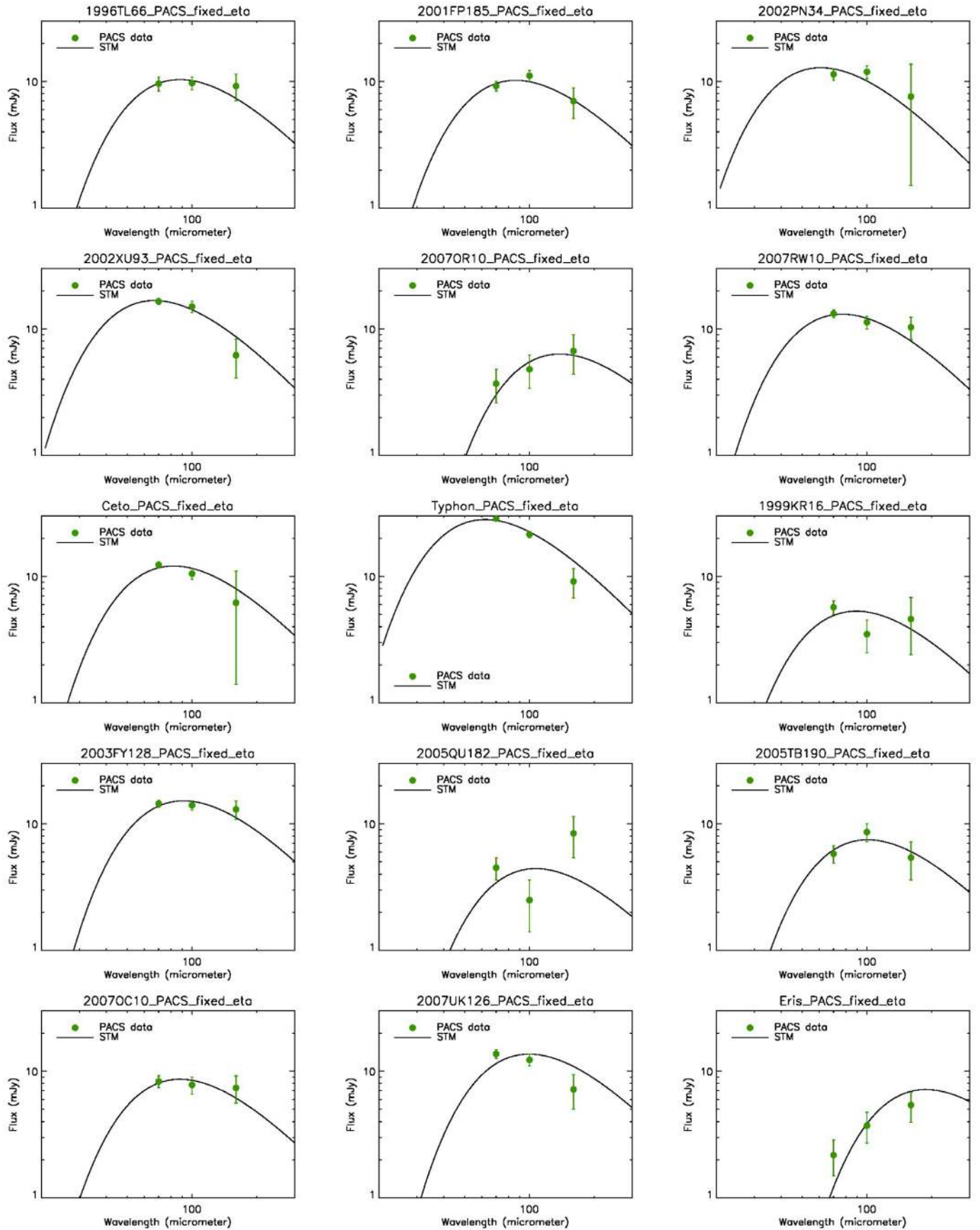


Fig. 1. Radiometric fixed- η fits for the objects observed only with *Herschel*-PACS.

In the best situation, photometrically calibrated observations are available at a variety of phase angles. In this case, correcting the observed V magnitudes for the heliocentric (r_h) and geocentric (Δ) distances provides $m_V(1, 1) = V - 5 \cdot \log(r \cdot \Delta)$. A linear fit of the $m_V(1, 1)$ magnitudes vs. phase angle α ($m(1, 1) = H_V + \beta \cdot \alpha$), taking into consideration measurement errors, then provides the phase coefficient β (mag/deg) and the absolute magnitude H_V , and their associated error bars. Whenever data are insufficient in V band but adequate in R band, we similarly and alternatively infer H_R , which by means of the thermal model will yield the red geometric albedo (p_R).

In the case when not enough data in either V or R are available, or if the above approach fails due to poor quality data, we adopt a mean $\beta = 0.10 \pm 0.04$ mag/deg which is the average value (excluding Pluto) from Belskaya et al. (2008). We then derive H magnitudes for each individual photometric measurement and use the weighted average result.

When photometrically-calibrated magnitudes are not available in the literature, we use astrometric observations compiled by MPC, as those include rough estimates of the optical magnitudes (most often in R band). The above approaches are then applied to this data, bearing in mind that individual V or R magnitudes reported in MPC data may have large (and systematically biased) uncertainties up to 0.5 mag (Romanishin & Tegler 2005).

When full lightcurve information is available (i.e. the amplitude is known and the lightcurve can be temporally phased to the *Herschel* measurements), the H magnitude is corrected accordingly. When the lightcurve amplitude (or an upper limit) is known, but the period is unknown or phasing is impossible, 88% of half peak-to-peak amplitude (i.e. $1\sigma = 68\%$ of the values of a sinusoid are within this range) is quadratically added to the uncertainty on H . Finally, if there is no lightcurve information, we assume peak-to-peak amplitude less than 0.2 mag, as based on Duffard et al. (2009), $\sim 70\%$ of the objects have a peak-to-peak amplitude less than this. In this case we quadratically add 0.09 mag (i.e. 88% of 0.2/2) to the H uncertainty. Absolute magnitudes quoted in Table 1 have been obtained as just described.

Note finally that in case we have to use R magnitudes (i.e. for 2007 OR₁₀, 2007 RW₁₀ and 1999 KR₁₆) modeling provides the R geometric albedo (p_R) instead of V albedo (p_V). p_R can be converted to p_V through:

$$p_V = p_R \times 10^{[(V-R)_\odot - (V-R)_{\text{obj}}]/2.5} \quad (3)$$

where $(V - R)_\odot = 0.36$ mag is the Sun's $V - R$, and $(V - R)_{\text{obj}}$ that of the object. We assume $(V - R)_{\text{obj}} = 0.55 \pm 0.11$, the mean value from Hainaut & Delsanti (2002) for 66 SDOs/Detached objects, except for 2007 OR₁₀ (see discussion for this object in Sect. 5.3).

4.3. Uncertainties

Within the framework of the thermal model, uncertainties on the fitted (D , p_V , η) parameters were obtained using a Monte-Carlo approach (see Mueller et al. 2011) in which 1000 synthetic datasets were randomly generated using the uncertainties in the measured fluxes. Note that the uncertainty in the H magnitude (and the ± 0.35 uncertainty in η , in the case of the “fixed- η ” approach) was also accounted for in the Monte-Carlo approach. Naturally, we eliminated those Monte-Carlo simulations which generated negative fluxes (or negative η). The diameter, albedo (and η) of each of the 1000 synthetic objects were determined, and their distributions were used to determine the error bars on these parameters. As outlined in Mueller et al. (2011), these

distributions are generally not Gaussian (especially the albedo distribution). Therefore, we adopted the median of the Monte-Carlo results as the nominal value, and asymmetric error bars to include the 68.2% of the results.

Figure 1 shows best fits for all objects in our sample using only the *Herschel*-PACS measurements. All these fits are “fixed- η ”. For the 8 objects that also have *Spitzer* fluxes, Fig. 2 shows best fits (“floating- η ”, except for Eris, which is not detected at 24 μm) for the combined *Herschel* and *Spitzer* measurements. In that Figure, the same best fit model is plotted twice, once (solid line) for the *Herschel* (r_h , Δ) conditions and once for the *Spitzer* (dashed line) conditions. In general, this shows that the model appropriately accounts for rather different *Herschel* vs. *Spitzer* fluxes associated to different r_h and Δ (e.g. Ceto, 2002 PN₃₄). Many of the fits shown in Figs. 1 and 2 are satisfactory, in that the model fits all data points within or close to the $1\text{-}\sigma$ error bars. However, in a number of cases, the fits are obviously bad (e.g. 1999 KR₁₆, 2005 QU₁₈₂, Typhon); in those cases, the data points are mutually inconsistent and the model is no more than a mere compromise between them. Given that the PACS green vs. blue observations (and the *Spitzer* vs. *Herschel* data) are not taken simultaneously, such behaviour could in principle result from rotational variability of the objects. An alternate physical explanation would be that the fluxes are affected by spectral features, e.g. depressing the 100- μm flux with respect to the 70- μm and 160- μm values, or more generally that our simple STM-like approach does not capture the complexity of the thermal emission. However, the discrepancies are often large and these explanations may not be quantitatively plausible. In those cases, we conclude that the error bars we have determined on the fluxes are probably underestimates of the true error bars, though we are unable to track down the reasons for that.

In the situation where the formal measurement errors are too small (or similarly that the model is not completely adequate), the above described Monte-Carlo method will underestimate the uncertainties on the solution parameters. To handle this problem, we adopted a “rescaled error bar” approach described in detail in Appendix B (Sect. B.1). Essentially, it consists of “inflating” the measurement error bars by a suitable factor before running the Monte-Carlo simulation. This approach was applied to the six objects for which the radiometric fit is poor (see Figs. 1 and 2): 1999 KR₁₆, 2002 PN₃₄, 2002 XU₉₃, 2005 QU₁₈₂, 2007 UK₁₂₆, and Typhon, with rescaling factors varying from 1.45 to 1.99. Fluxes for the remaining nine objects are satisfactorily fit within the $1\text{-}\sigma$ flux uncertainties and did not require any adjustment of the measurement errors. We finally stress that the diameter, albedo, and beaming factor values and their uncertainties reported in the next section are obtained in the framework of the hybrid STM, which may have its own limitations (see Harris 2006, for a discussion in the case of NEOs). More physical models (e.g. TPM) may lead to somewhat different values and error bars, as illustrated by Müller et al. (2010) in the case of a few objects observed in the Science Demonstration Phase (SDP) of the “TNOs are cool” programme.

5. Results and discussion

5.1. General results

Results of the model fits in terms of the objects diameter, albedo and beaming factor are gathered in Table 5. When *Spitzer*-MIPS measurements are available (8 objects), the model was run twice, once considering the PACS fluxes only, and once combining PACS and MIPS. As illustrated in Table 5, these two

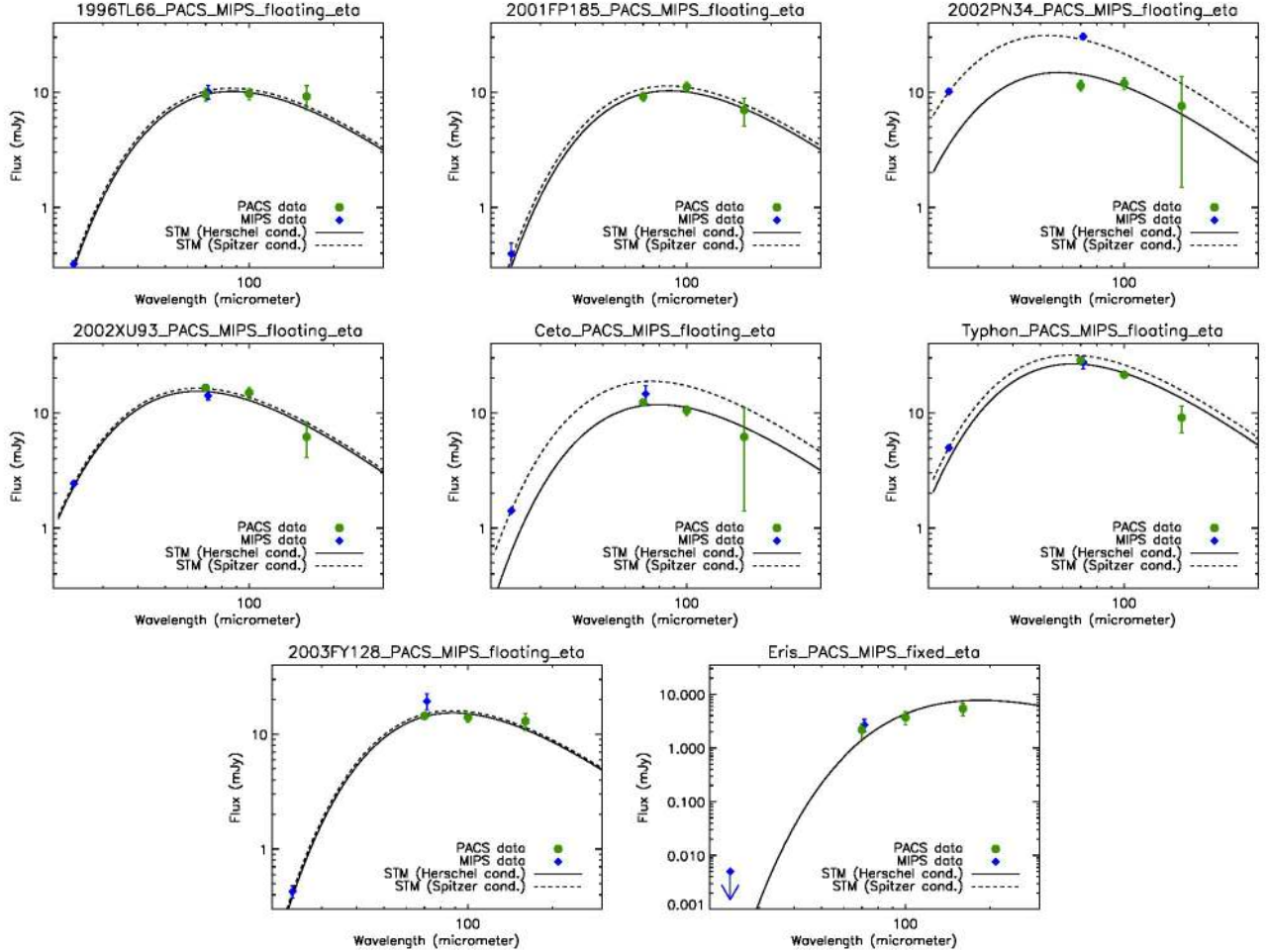


Fig. 2. Radiometric hybrid-STM fits for the objects observed with *Spitzer*-MIPS and *Herschel*-PACS. The best fit is plotted for the *Herschel* (r_h , Δ) conditions (solid line) and for the *Spitzer* conditions (dashed line).

fitting options give consistent solutions within error bars. The PACS+MIPS solution is always adopted as the preferred one (outlined in bold face in Table 5), as it (i) provides reduced error bars (ii) permits the determination of the beaming factor.

Table 5 includes first size/albedo determination for 9 objects (4 SDO and 5 detached objects). Six of them are based on PACS-only measurements (2007 OR₁₀, 2007 RW₁₀, 1999 KR₁₆, 2005 QU₁₈₂, 2007 OC₁₀, and 2007 UK₁₂₆), and the remaining three make use of PACS plus unpublished-MIPS data (2001 FP₁₈₅, 2002 XU₉₃, and 2003 FY₁₂₈). Published sizes and albedos exist for the other 6 objects of our sample (1996 TL₆₆, 2002 PN₃₄, Ceto, Typhon, 2005 TB₁₉₀ and Eris) but we here present fluxes for these objects at wavelengths not observed before (i.e. 100 μ m and 160 μ m), and the combination with earlier measurements leads to improved estimations of sizes, albedos, and beaming factors (see Table 5).

The V geometric albedos for our targets vary from 3.8% (2002 XU₉₃) to 84.5% (Eris), with an unweighted mean value of $11.2 \pm 7.6\%$ excluding Eris. If weighted by the relative errors (i.e. $1/(\sigma/p_V)^2$), the mean albedo is $6.4 \pm 6.3\%$ (for σ we used the mean of upward and downward uncertainties on p_V). This error bar on the mean albedo includes the dispersion of the albedo measurements and their individual RMS errors. It is dominated by the dispersion between individual measurements, so it has a limited significance. This variation of geometric albedos can be seen in Fig. 3-left. For SDOs, there is a lack of albedos $>20\%$

and a clustering in the [0–5%] range. In contrast, detached objects in our sample all have albedos $>5\%$, with a peak in the [10–20%] range. The unweighted/weighted mean is 6.9/5.2% for the SDOs and 17.0/12.3% for detached objects excluding Eris.

Diameters vary from 112 km (2002 PN₃₄) to 2454 km (Eris), with a remarkably uniform distribution (Fig. 3, right). However, the distribution of diameters is seemingly different between SDOs and detached objects. SDO diameters are smaller than 400 km, except for an outlier at 1280 km (2007 OR₁₀), while all detached objects are larger than 200 km. This apparent tendency of detached objects to be larger than SDOs is, however, probably an effect of the discovery bias (see discussion in Sect. 2), as detached objects are typically discovered at larger heliocentric distances than SDOs.

Except for Eris, where the “floating η ” fit fails, the combination of *Spitzer* and *Herschel* data allows us to determine the beaming factor for 7 objects (6 SDO and 1 detached – see Table 5 –). The (weighted by absolute errors) mean- η obtained from these results is 1.14 ± 0.15 . This is fully consistent with the mean 1.20 ± 0.35 η -value derived from the *Spitzer* dataset (Stansberry et al. 2008) and justifies the use of this mean value for those cases where η cannot be determined. Beaming factors only barely larger than ~ 1 (as opposed to $\eta \gg 1$) indicate that KBOs in general and our sample objects in particular are close to the slow rotator regime (i.e. STM), which is a remarkable result

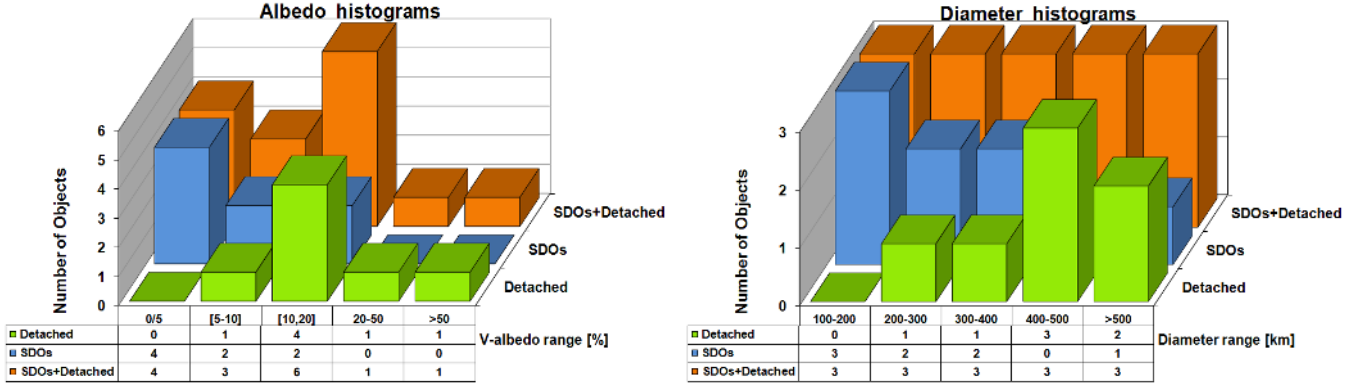


Fig. 3. *Left:* geometric albedo histograms for SDOs/Detached, SDOs and detached objects. *Right:* diameter histograms for SDOs/Detached, SDOs and detached objects.

Table 5. Radiometric fit results for the objects sample.

Object	Data	D [km]	p_v [%]	η	Class.
(15874) 1996 TL ₆₆	PACS	341 ± 40	11.0 ^{+3.8} _{-2.5}	1.20 ± 0.35*	SDO
(15874) 1996 TL₆₆	PACS/MIPS	339 ± 20	11.0 ^{+2.1} _{-1.5}	1.15 ^{+0.08} _{-0.05}	SDO
(82158) 2001 FP ₁₈₅	PACS	329 ± 42	4.7 ^{+1.3} _{-1.0}	1.20 ± 0.35*	SDO
(82158) 2001 FP₁₈₅	PACS/MIPS	332 ⁺³¹ ₋₂₄	4.6 ± 0.7	1.23 ^{+0.24} _{-0.19}	SDO
(73480) 2002 PN ₃₄	PACS	110 ± 12	5.2 ^{+1.3} _{-0.9}	1.20 ± 0.35*	SDO
(73480) 2002 PN₃₄	PACS/MIPS	112 ± 7	4.9 ± 0.6	1.02 ^{+0.07} _{-0.09}	SDO
(127546) 2002 XU ₉₃	PACS	173 ± 20	3.5 ^{+0.9} _{-0.6}	1.20 ± 0.35*	SDO
(127546) 2002 XU₉₃	PACS/MIPS	164 ± 9	3.8 ± 0.4	1.12 ^{+0.05} _{-0.08}	SDO
2007 OR₁₀	PACS	1280 ± 210	18.5 ^{+7.6} _{-5.2} ★	1.20 ± 0.35*	SDO
2007 RW₁₀	PACS	247 ± 30	8.3 ^{+6.8} _{-3.9} ★	1.20 ± 0.35*	SDO
(65489) Ceto	PACS	300 ± 39	4.9 ^{+1.6} _{-1.0}	1.20 ± 0.35*	SDO
(65489) Ceto	PACS/MIPS	281 ± 11	5.6 ± 0.6	1.04 ± 0.05	SDO
(42355) Typhon	PACS	175 ± 17	4.9 ^{+1.1} _{-0.8}	1.20 ± 0.35*	SDO
(42355) Typhon	PACS/MIPS	185 ± 7	4.4 ± 0.3	1.48 ± 0.07	SDO
(40314) 1999 KR₁₆	PACS	254 ± 37	20.4 ^{+7.0} _{-5.0} ★	1.20 ± 0.35*	DO
(120132) 2003 FY ₁₂₈	PACS	479 ⁺⁵⁵ ₋₆₇	7.2 ^{+2.7} _{-1.5}	1.20 ± 0.35*	DO
(120132) 2003 FY₁₂₈	PACS/MIPS	460 ± 21	7.9 ± 1.0	1.07 ± 0.08	DO
2005 QU₁₈₂	PACS	416 ± 73	32.8 ^{+16.0} _{-10.9}	1.20 ± 0.35*	DO
(145480) 2005 TB₁₉₀	PACS	464 ± 62	14.8 ^{+5.1} _{-3.6}	1.20 ± 0.35*	DO
2007 OC₁₀	PACS	309 ± 37	12.7 ^{+4.0} _{-3.8}	1.20 ± 0.35*	DO
(229762) 2007 UK₁₂₆	PACS	599 ± 77	16.7 ^{+3.8} _{-2.8}	1.20 ± 0.35*	DO
(136199) Eris	PACS	2420 ⁺¹⁰⁰ ₋₁₁₉	86.7 ^{+9.8} _{-6.3}	1.20 ± 0.35*	DO
(136199) Eris	PACS/MIPS	2454 ± 117	84.5 ± 8.8	1.20 ± 0.35*	DO

Notes. These are the results obtained by the application of an hybrid-STM to the fluxes obtained by *Herschel*-PACS (with *Spitzer*-MIPS data when are available). Preferred results for each target are in bold. Object: SDO or detached object observed with *Herschel*-PACS (and *Spitzer*-MIPS when available). Data: PACS, model results using only fluxes from *Herschel*-PACS. PACS/MIPS, model results using fluxes from *Herschel*-PACS and *Spitzer*-MIPS. D [km]: diameter and uncertainty, in kilometres, obtained from the thermal model. p_v [%]: geometric albedo and uncertainty, in V -band, obtained from the thermal model. ★ Indicates geometric albedos derived from H_R magnitudes instead of H_V , (i.e., p_r [%]). η : beaming factor from the thermal model application. * Objects for which there are not *Spitzer*-MIPS fluxes available, in this case we assume a mean η value to perform the radiometric fits. Class., dynamical classification following Gladman et al. (2008). SDO = scattered disc object, DO = detached object.

given the very low temperatures prevailing on these objects and their usually short rotation periods. Except in the unlikely situation where they are all seen pole-on, this implies very low thermal inertia and/or very large surface roughness. Lellouch et al. (2011) determine the thermal inertia of Charon's surface to be $\Gamma = 10\text{--}20 \text{ J m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$ (MKS) and find this to be equivalent to $\eta = 1.21\text{--}1.40$. Yet Charon is a slow rotator (6.4 day) and a rough scaling indicates that the same η range, applied e.g. to Haumea or Orcus, would be representative of even much smaller thermal inertias ($\Gamma = 0.5\text{--}3$ MKS). Hence a general conclusion is that unless they are very rough, KBO surfaces must have very low thermal conductivity, suggesting a high degree of surface porosity. Similar thermal inertias and η 's for KBOs were obtained in Müller et al. (2010).

5.2. Comparison with earlier results

Six objects of our sample (1996 TL₆₆, 2002 PN₃₄, Ceto, Typhon, 2005 TB₁₉₀ and Eris) have previously published sizes/albedos. We here briefly compare results for the first five, and discuss Eris in more detail in next subsection. Note that 2007 UK₁₂₆ has been reported as binary system (Noll et al. 2009), but there is no mass estimation for this object, for this reason so we do not discuss it here.

(15874) 1996 TL₆₆. Our preferred solution for this SDO ($D = 339 \pm 20$ km, $p_v = 11.0^{+2.1}_{-1.5}\%$, $\eta = 1.15^{+0.08}_{-0.05}$) is at odds with the Stansberry et al. 2008 results ($D = 575^{+116}_{-115}$ km, $p_v = 3.5^{+2.0}_{-1.0}\%$, $\eta = 1.8 \pm 0.3$) based on *Spitzer*-MIPS fluxes at 24 and 70 μm . Our reprocessing of these data leads to very different fluxes at 24 μm

(0.32 mJy vs. 0.38 mJy in [Stansberry et al. 2008](#)) and especially at 70 μm (10.1 mJy vs. 22 mJy). Fitting these revised *Spitzer* fluxes alone gives a best fit ($D = 328 \text{ km}$, $p_V = 11.8\%$, $\eta = 1.12$) in excellent agreement with our preferred solution.

(73480) 2002 PN₃₄. Although the 70 μm fluxes from *Spitzer* and *Herschel* are very different (Fig. 2), this can be ascribed to the different observing distances. Our preferred results are: $D = 112 \pm 7 \text{ km}$, $p_V = 4.9 \pm 0.6\%$, $\eta = 1.02^{+0.07}_{-0.09}$, in a good agreement with [Stansberry et al. \(2008\)](#) results: ($D = 120 \pm 10 \text{ km}$, $p_V = 4.3^{+0.8}_{-0.7}\%$, $\eta = 1.10^{+0.16}_{-0.15}$). This object is the smallest one in our SDOs/Detached sample.

(65489) Ceto/Phorcys is a binary SDO, previously observed with *Spitzer*-MIPS ([Grundy et al. 2007](#); [Stansberry et al. 2008](#)). Model fits indicate that the optimum model ($D = 281 \pm 11 \text{ km}$, $p_V = 5.6 \pm 0.6\%$, $\eta = 1.04 \pm 0.05$) matches the 24 μm flux but somewhat overestimates the *Spitzer* 70 μm flux, indicative of a colder object than the *Spitzer* data would suggest. It is therefore not surprising that the *Spitzer*-only solution of [Stansberry et al. \(2008\)](#) has a lower η ($0.86^{+0.10}_{-0.09}$), lower D ($230^{+19}_{-18} \text{ km}$) and higher p_V ($7.7^{+1.4}_{-1.1}\%$).

[Grundy et al. \(2007\)](#) estimate a mass of $(5.41 \pm 0.42) \times 10^{18} \text{ kg}$ for the Ceto/Phorcys system. Using an equivalent diameter of $218^{+20}_{-22} \text{ km}$, they obtain a bulk density of $1.37^{+0.66}_{-0.32} \text{ g cm}^{-3}$. We derive a smaller bulk density of $0.64^{+0.16}_{-0.13} \text{ g cm}^{-3}$ due to our larger equivalent diameter ($D = 281 \text{ km}$ which gives $D_{\text{Ceto}} = 223 \pm 10 \text{ km}$, and $D_{\text{Phorcys}} = 171 \pm 10 \text{ km}$, assuming the same albedo for the two components and $\Delta m = 0.58 \pm 0.03 \text{ mag}$). This low bulk density is compatible with a porous surface, which is also supported by the very low $\eta = 1.04$ value.

(42355) Typhon/Echidna is a binary SDO. Our preferred results are $D = 185 \pm 7 \text{ km}$, $p_V = 4.4 \pm 0.3\%$, $\eta = 1.48 \pm 0.07$, consistent with the [Stansberry et al. \(2008\)](#) solution obtained by applying a fixed $\eta = 1.2 \pm 0.35$ model to the 24 μm flux ($D = 174^{+16}_{-18} \text{ km}$, $p_V = 5.1^{+1.2}_{-0.8}\%$). In contrast, these results are inconsistent with the preliminary *Herschel* results ($D = 138 \pm 9 \text{ km}$ and $p_V = 8.0 \pm 1.0\%$), based on SDP data ([Müller et al. 2010](#)). The latter observations were performed in chop-nod mode (less sensitive than scan-map for point sources) and led to lower 70 and 100 μm fluxes and no detection at 160 μm .

[Grundy et al. \(2008\)](#) obtain a mass of $(9.49 \pm 0.52) \times 10^{17} \text{ kg}$ for this binary system. Using an equivalent diameter of $179^{+16}_{-18} \text{ km}$, they obtain a bulk density of $0.44^{+0.44}_{-0.17} \text{ g cm}^{-3}$. We derive a nominally even smaller (but compatible within error bars) bulk density of $0.36^{+0.08}_{-0.07} \text{ g cm}^{-3}$ from a slightly larger equivalent diameter ($D = 185 \text{ km}$, i.e. $D_{\text{Typhon}} = 162 \pm 7 \text{ km}$, and $D_{\text{Echidna}} = 89 \pm 6 \text{ km}$, assuming same albedo and $\Delta m = 1.30 \pm 0.06 \text{ mag}$). Again, this extremely low bulk density points to a porous body.

(145480) 2005 TB₁₉₀. This detached object was not observed by *Spitzer*-MIPS, but was already measured in chop-nod mode by *Herschel*. Our new results, using a fixed- η mode ($D = 464 \pm 62 \text{ km}$, $p_V = 14.8^{+5.1}_{-3.6}\%$) are reasonably consistent (to within 1- σ) with the preliminary values published by [Müller et al. \(2010\)](#) ($D = 375 \pm 45 \text{ km}$, $p_V = 19.0 \pm 5.0\%$).

5.3. Two large objects, 2007 OR₁₀ and Eris

2007 OR₁₀. Its H_R magnitude of ~ 2 indicates that this very distant object (currently at 86.3 AU) must be one of the largest TNOs, unless it exhibits a very high albedo. [Brown et al. \(2011\)](#) recently reported that its spectrum is markedly red in the near-infrared and shows features due to water ice. This is an unusual combination as most KBOs with water ice absorptions

have neutral colors, but this characteristic is shared by Quaoar. Although their data are insufficient to show a detection of methane ice, [Brown et al. \(2011\)](#) used the analogy with Quaoar, where methane ice is present ([Schaller & Brown 2007a](#)), to suggest that the red color of 2007 OR₁₀ is due to irradiation of small amounts of methane ice. They further assumed an albedo equal to that of Quaoar (nominally 0.18 for an adopted Quaoar radius of 960 km, but allowing for 50% uncertainties), and showed, based on the [Schaller & Brown \(2007b\)](#) sublimation model, that 2007 OR₁₀ is in a similar volatile retention regime as Quaoar, with the main volatile species (N_2 , CO, CH_4) being marginally stable over the solar system age.

2007 OR₁₀ is clearly detected in the three PACS channels. In the lack of V measurements, we assumed $H_R = 1.96 \pm 0.16 \text{ mag}$ based on the fit of eight good quality R -measurements from MPC data (see Table 1). A fixed- η fit is satisfactory (Fig. 1), providing $D = 1280 \pm 210 \text{ km}$, $p_R = 18.5^{+7.6}_{-5.2}\%$. This puts the object in the Charon, Makemake, Haumea, etc. size class, i.e. a plausible candidate for dwarf planet status. To convert p_R to p_V we use Eq. (3) from Sect. 4.2, but use Quaoar’s $V - R$ value = 0.67 ± 0.02 ([Fornasier et al. 2004](#)). This yields $p_V = 13.9^{+5.7}_{-3.9}\%$, nicely consistent with the value assumed by [Brown et al. \(2011\)](#). 2007 OR₁₀ thus indeed appears as a sibling to Quaoar, probably of even larger size.

(136199) Eris. Although Eris was observed by *Spitzer*, it was not detected at 24 μm (with a 0.005 mJy upper limit), preventing us from determining its beaming factor. Assuming therefore $\eta = 1.20 \pm 0.35$, we obtain a best fit solution for $D = 2454 \pm 117 \text{ km}$, $p_V = 84.5 \pm 8.8\%$. Using the mass determined by [Brown et al. \(2007\)](#) – recomputed in [Grundy et al. \(2011\)](#) – for the Eris/Dysnomia system ($(1.688 \pm 0.035) \times 10^{22} \text{ kg}$) we obtain a bulk density of $2.23^{+0.41}_{-0.33} \text{ g cm}^{-3}$, assuming the same albedo for Eris and Dysnomia ($D_{\text{Eris}} = 2434 \pm 117 \text{ km}$, and $D_{\text{Dysnomia}} = 316 \pm 23 \text{ km}$). It is probably more realistic to assume that Dysnomia’s surface is much darker than Eris’. Assuming for definiteness a 5 times lower albedo, we obtain $D_{\text{Eris}} = 2356 \pm 117 \text{ km}$ and $D_{\text{Dysnomia}} = 685 \pm 50 \text{ km}$, yielding a global density of $2.40^{+0.46}_{-0.37} \text{ g cm}^{-3}$, similar to the [Brown et al. \(2007\)](#) value ($2.3 \pm 0.3 \text{ g cm}^{-3}$).

Near-IR spectroscopy ([Tegler et al. 2010](#); [Merlin et al. 2009](#); [Brown et al. 2005](#)) indicates that Eris’ surface composition is very similar to Pluto’s, with the presence of methane ice along with another dominant ice, presumably nitrogen, suggestive of a high albedo. Prior to our measurements, Eris’ size and albedo have been determined by several groups and methods. The first measurement was achieved by [Bertoldi et al. \(2006\)](#) who used IRAM thermal observations at 1200 μm and obtained $D = 3000^{+300}_{-100} \text{ km}$ and $p_V = 60 \pm 10\%$. Subsequently, [Brown et al. \(2006\)](#) estimated $D = 2400 \pm 100 \text{ km}$, $p_V = 86 \pm 7\%$ from direct imaging with the *Hubble* Space Telescope. Based on the *Spitzer* 70 μm flux, [Stansberry et al. 2008](#) obtained $D = 2657^{+216}_{-209} \text{ km}$, $p_V = 68.9^{+12.2}_{-10.0}\%$ from *Spitzer*-MIPS and hybrid-STM fit. Within uncertainties, our results agree with all these values except with those of [Bertoldi et al. \(2006\)](#), which overestimate the size and underestimate the albedo. Most recently, a stellar occultation by Eris on November 6th 2010 provided a very accurate determination of Eris’ diameter and albedo: $D = 2326 \pm 12 \text{ km}$, $p_V = 96^{+9}_{-4}\%$ ([Sicardy et al. 2011](#)), assuming a spherical shape. (Note however that allowing for elliptical shape, [Sicardy et al.](#) find a broader range of solutions, 68.3% (1- σ) of which have an effective diameter of $2330 \pm 180 \text{ km}$.) Eris’ diameter is thus indistinguishable from Pluto’s given error bars on both, supporting the idea that Eris is a Pluto twin, with an

even brighter surface, presumably due to a collapsed atmosphere at aphelion.

At face value and given error bars, our result on Eris' diameter agrees nicely with that of Sicardy et al. (2011), especially if we assume that Dysnomia is intrinsically much darker than Eris. Similarly, our density for the system is in line with theirs ($2.52 \pm 0.05 \text{ g cm}^{-3}$). However, the consistency is actually not complete. Sicardy et al. (2011) reanalyzed the *Spitzer* 70 μm and IRAM 1200 μm fluxes in the light of their determined diameter and albedo. They considered both a standard thermal model (STM) and an isothermal latitude model (ILM), introducing an “ η ” ($=\eta_R$) parameter describing exclusively surface roughness effects (and ranging from $\eta_R = 1.0$ – no roughness – to $\eta_R = 0.7$ – large roughness –). In this framework, the only free parameter of their thermal model was the phase integral q . They found that the thermal measurements implied $q = 0.49$ – 0.66 for the STM case (fully consistent with the value of Saturn's brightest satellites), but an implausible $q = 0$ – 0.24 for the ILM. On this basis, the STM was strongly favored, implying either a pole-on orientation or a negligible thermal inertia. The inconsistency with our analysis resides in the fact that we assumed $\eta = 1.20 \pm 0.35$ and that our p_V solution implies $q = 0.75$, according to the assumed Brucker et al. (2009) expression. Another way of seeing this is to note that if we now assume the two limiting STM cases considered by Sicardy et al. 2011 (i.e. $q = 0.49$, $\eta_R = 1.0$, and $q = 0.66$, $\eta_R = 0.7$) and re-fit the PACS + MIPS data, we obtain best fit diameters of 2034 km and 2139 km respectively, and V-albedos larger than 100% in the two cases, inconsistent with the occultation results. Ultimately, the discrepancy can be traced to the fact that Sicardy et al. (2011) included the IRAM 1200 μm flux in their model, which as they noted tends to indicate warmer temperatures than the *Spitzer* 70 μm flux, while on the contrary our best fit model tends to underestimate the latter. The resolution of this problem will require a simultaneous fits of all datasets, considering in particular (i) non-spherical shapes (ii) separate thermal models for Eris and Dysnomia and (iii) more elaborate thermophysical models in which the thermal inertia, surface roughness and spin orientation are free parameters. This study is deferred to a subsequent paper (Kiss et al., in prep.-b). Note finally that the interpretation of thermal observations of a volatile-covered body such as Eris is expected to be even more complex than presented here. An additional complication is that volatile transport will result in surface variegation, i.e. multiple surface albedos. This is demonstrated in the case of Pluto, which does show large albedo spatial variations and whose thermal data require three-terrain model (Lellouch et al. 2011; Mommert et al. 2012). Another example is Makemake, the visual appearance of which is unknown but for which a two-terrain model is required to fit the radiometric data (Lim et al. 2010).

5.4. Search for correlations

5.4.1. Description of the method

Using Spearman-rank correlation coefficient (Spearman 1904), also known as Spearman- ρ , we have examined our results for correlations between albedo (p_V), beaming factor (η), diameter (D), absolute magnitude (H), color ($B - R$), perihelion distance (q), orbital inclination (i), semi-major axis (a), and heliocentric distance at the time of observation (r_h).

Spearman- ρ is distribution-free and less sensitive to outliers than most other methods but, like others, treats data-points as “exact” and does not take into account their possible error bars. Any variations in the measured data points within their

error bars, may change the correlation coefficient, however. Furthermore, each correlation coefficient has its own confidence interval, which depends on the number of data points and on the magnitude of the correlation. We use procedures described in Appendix B (Sect. B.2) and in Peixinho et al. (2004) to deal with these effects to obtain Spearman- ρ values that take into account the error bars.

We call correlations “strong” when $|\rho| \geq 0.6$. Efron & Tibshirani (1993) analyze the evidence for correlation with the follow criteria (where CL is the confidence level defined in Appendix B): $CL \geq 99\%$ ($p \leq 0.010$): very strong evidence of correlation; and $CL \geq 99.7\%$ ($p \leq 0.003$), the “standard” 3σ significance: clear correlation. We restrict ourselves to the cases with $CL \geq 99.5\%$ ($p \leq 0.005$), i.e. at least 2.8σ confidence.

5.4.2. Correlations analysis

Based on the previously described methods, the strongest and/or more interesting correlations are shown in Table 6. These are given for the whole sample (including or excluding Eris), and for SDOs and detached objects separately. Before discussing them, we stress that results must be taken with care because of small number statistics. In general, more significant correlations are found for SDOs than for detached objects.

“Clear correlations” ($\geq 99.7\%$) in Table 6 are seen between D and H (negative correlation, 3.0σ), p_V and H (negative, 4.2σ), D and r_h (positive, 4.9σ), p_V and r_h (positive, 3.8σ). The first two anticorrelations are a simple consequence of Eq. (1), with no physical implication. The positive correlations between D and r_h , and between p_V and r_h , are most probably biases due to object selection criterion and discovery bias, as discussed in Sect. 2.

Additional “clear” or “very strong evidence” ($\geq 99\%$) for positive correlations are found between D and q (3.4σ) and p_V and q (2.9σ) (Fig. 4). There is no a priori relationship between diameter, albedo and perihelion distance, hence these correlations could plausibly be real, as discussed below. However, they could also reflect biases due to the correlation between q and r_h (at 3.9σ for our sample, see Table 6), i.e. the discovery bias discussed in Sect. 2. On the other hand, it is noteworthy that no high albedo objects (e.g. $p_V > 10\%$) are seen at small heliocentric or perihelion distance (≤ 30 AU), which should not be a bias. Note that when SDOs and detached objects are treated separately, the D vs. q correlation remains significant at 2σ only, while the p_V and q correlation essentially vanishes. Correlations also decrease (marginally) if Eris is excluded from the sample.

Based on *Spitzer* measurements of about 50 objects, Stansberry et al. (2008) noted the apparent positive correlation between p_V and q (3.5σ in their case). While recognizing the above discovery bias, they proposed it to be real, offering two explanations. First, objects near the Sun tend to experience higher temperatures, hence may be subject to increased sublimation of their intrinsically bright ices. Conversely, increased UV-photolysis and solar wind radiolysis associated with the low heliocentric/perihelion distances may preferentially darken the surfaces of these objects. It seems more difficult to find a physical explanation for an hypothetical correlation between diameter and perihelion distance, especially because the current orbits of the SDOs/Detached objects tell us little if anything about the formation region. This apparent correlation is most probably a bias, as discussed above. Note also that unlike Stansberry et al. (2008) we do not find any (even tentative) correlation between p_V and the semi-major axis a ($\rho = 0.21$, 0.8σ , see Table 6).

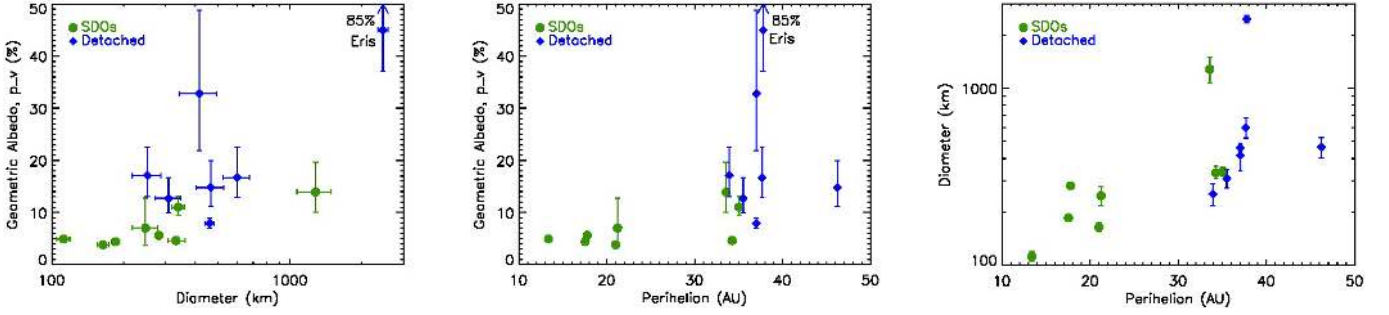


Fig. 4. Plots illustrating the three more interesting correlations with $CL \geq 99.5\%$ ($\geq 2.8\sigma$) in our results. From left to right: albedo vs. diameter, albedo vs. perihelion distance, and diameter vs. perihelion distance (Eris is out of the albedo scale in the first two panels, but its albedo is indicated).

Table 6. Summary of correlations with diameter and geometric albedo.

Variables	Class	Without error bars		Accounting for data error bars		
		n	ρ	$\langle \rho \rangle_{-\sigma}^{+\sigma}$	p	$CL(\%)$ (σ_p)
D vs. H	SDOs+DOs	15	-0.93	$-0.74_{-0.19}^{+0.48}$	0.00244	99.8 (3.03)
	SDOs+DOs*	14	-0.91	$-0.68_{-0.19}^{+0.37}$	0.00989	99.0 (2.58)
	SDOs	8	-0.93	$-0.80_{-0.14}^{+0.38}$	0.0281	97.2 (2.20)
	DOs	7	-0.86	$-0.53_{-0.29}^{+0.49}$	0.243	75.7 (1.17)
D vs. r_h	SDOs+DOs	15	0.93	$0.92_{-0.11}^{+0.05}$	0.000001	>99.9 (4.91)
	SDOs+DOs*	14	0.92	$0.90_{-0.14}^{+0.06}$	0.000010	>99.9 (4.42)
	SDOs	8	0.98	$0.96_{-0.09}^{+0.03}$	0.00134	99.9 (3.21)
	DOs	7	0.71	$0.74_{-1.26}^{+0.25}$	0.0782	92.2 (1.76)
	DOs*	6	0.54	$0.58_{-0.49}^{+0.26}$	0.256	74.4 (1.14)
D vs. q	SDOs+DOs	15	0.81	$0.79_{-0.22}^{+0.11}$	0.000594	>99.9 (3.43)
	SDOs+DOs*	14	0.78	$0.76_{-0.28}^{+0.14}$	0.00270	99.7 (3.00)
	SDOs	8	0.81	$0.80_{-0.23}^{+0.11}$	0.0264	97.4 (2.22)
	DOs	7	0.86	$0.80_{-1.39}^{+0.20}$	0.0512	94.9 (1.95)
	DOs*	6	0.89	$0.80_{-0.33}^{+0.13}$	0.106	89.4 (1.61)
p_V vs. H	SDOs+DOs	15	-0.88	$-0.87_{-0.06}^{+0.11}$	0.000027	>99.9 (4.20)
	SDOs+DOs*	14	-0.85	$-0.84_{-0.07}^{+0.13}$	0.000186	>99.9 (3.74)
	SDOs	8	-0.81	$-0.77_{-0.15}^{+0.34}$	0.036888	96.3 (2.09)
	DOs	7	-0.64	$-0.66_{-0.22}^{+0.45}$	0.128142	87.2 (1.52)
p_V vs. D	SDOs+DOs	15	0.71	$0.71_{-0.22}^{+0.14}$	0.004045	99.6 (2.88)
	SDOs+DOs*	14	0.65	$0.64_{-0.24}^{+0.16}$	0.015648	98.4 (2.42)
	SDOs	8	0.71	$0.68_{-0.42}^{+0.20}$	0.078503	92.1 (1.76)
	DOs	7	0.25	$0.32_{-0.96}^{+0.57}$	0.483703	51.6 (0.70)
p_V vs. r_h	SDOs+DOs	15	0.87	$0.83_{-0.14}^{+0.08}$	0.000126	>99.9 (3.83)
	SDOs+DOs*	14	0.84	$0.79_{-0.16}^{+0.10}$	0.001327	99.9 (3.21)
	SDOs	8	0.69	$0.65_{-0.48}^{+0.23}$	0.098781	90.1 (1.65)
	DOs	7	0.68	$0.69_{-1.19}^{+0.28}$	0.105315	89.5 (1.62)
p_V vs. q	SDOs+DOs	15	0.75	$0.71_{-0.19}^{+0.12}$	0.003965	99.6 (2.88)
	SDOs+DOs*	14	0.71	$0.68_{-0.23}^{+0.15}$	0.010510	98.9 (2.56)
	SDOs	8	0.48	$0.47_{-0.49}^{+0.31}$	0.251698	74.8 (1.15)
	DOs	7	0.25	$0.36_{-0.72}^{+0.45}$	0.430091	57.0 (0.79)
p_V vs. a	SDOs+DOs	15	0.24	$0.21_{-0.32}^{+0.28}$	0.449038	55.1 (0.76)
p_V vs. e	SDOs+DOs	15	-0.41	$-0.39_{-0.22}^{+0.28}$	0.154918	84.5 (1.42)
p_V vs. i	SDOs+DOs	15	0.05	$0.09_{-0.38}^{+0.36}$	0.769100	23.1 (0.29)
r_h vs. q	SDOs+DOs	15	0.81	$0.84_{-0.20}^{+0.09}$	0.000084	>99.9 (3.93)

Notes. Spearman-rank correlation tests given the main correlations between the various magnitudes. * Indicates that Eris is excluded. n : number of data points. ρ : Spearman-rank correlation without data error bars. $\langle \rho \rangle_{-\sigma}^{+\sigma}$: Spearman-rank correlation accounting for data error bars. p : significance p -value of the correlation. $CL(\%)$: confidence level defined as $(1-p) \cdot 100\%$. σ_p : Gaussian- σ equivalent to the significance p -value (see Appendix B for details). D : diameter. r_h : heliocentric distance at the time of observation. a : orbital semi-major axis. e : orbital eccentricity. i : orbital inclination with respect to the ecliptic plane. q : perihelion. p_V : V-band geometric albedo. The last line shows that r_h and q are strongly correlated in our sample.

We find a very strong correlation between albedo and diameter (p_V vs. D) when SDOs are included, in particular for the whole sample at 2.9σ significance (see Fig. 4). This result was obtained by Stansberry et al. (2008) for KBOs (defined there as any object but Centaurs) but was not robust against small changes in the classification. This correlation implies a trend for larger objects having higher albedos. An explanation could invoke the fact that larger objects can retain bright ices (released either by collision or intrinsic activity) more easily than small objects do. Eris follows this tendency, although its extremely high albedo puts it as an outlier in the plot of Fig. 4. An important aspect here is that there are no small objects (≤ 300 km) with high albedo ($\geq 10\%$). This cannot be a bias, as such objects would have been targeted in our sample, yet poorly detected. Note that if objects with albedos $\geq 10\%$ are to be associated with the presence of surface ices, then such ices should be only moderately volatile (i.e. CH_4 or less), as volatile retention models (Schaller & Brown 2007b; Brown et al. 2011) show that only the largest (≥ 1000 – 1500 km) bodies can retain the most volatile ices such as N_2 or CO over the solar system age.

Finally, we do not detect any correlation between diameter/albedo and color, or inclination, nor between the beaming factor η with any parameter (though the sample is limited to 7 objects in the latter case).

In summary, in spite of the relatively small sample covered in this paper, we find three possible correlations (i.e. p_V vs. D , p_V vs. q , and D vs. q), of which at least the first one – large objects tend to have brighter surfaces than small objects – is real and may be physically explained. More subtle correlations may be found, but with lower significance, and larger datasets will be required for confirmation.

6. Summary

We have determined albedos/sizes of 8 SDOs and 7 detached objects using *Herschel*-PACS fluxes measurements at 70, 100 and 160 μm and *Spitzer*-MIPS fluxes at 23.68 and 71.42 μm when available. The main results, which include nine first determinations, are summarized hereafter:

- Diameters range from 100 to 2400 km. The overall diameter distribution in our sample is remarkably uniform, but apparently different for SDOs vs. detached objects. This difference might however just reflect a sample/discovery bias, as our sample favors large objects at large heliocentric distances, and detached objects are typically discovered at larger distances than SDOs.
- V -geometric albedos range from 3.8 to 84.5%. Unweighted mean albedo for the whole sample is 11.2% and 6.9/17.0% for the SDOs/Detached (excluding Eris) respectively. There is a lack of albedos $>20\%$ with a peak in the [0–5%] range for SDOs. Detached objects have albedos $>5\%$, with a peak in the [10–20%] range.
- We re-determine bulk densities of three binary systems, based on our estimated sizes and published masses: Ceto/Phorcys ($0.64^{+0.16}_{-0.13}$ g cm^{-3}), Typhon/Echidna ($0.36^{+0.08}_{-0.07}$ g cm^{-3}), and Eris/Dysnomia ($2.40^{+0.46}_{-0.37}$ g cm^{-3}).
- Beaming factor (η), determined from thermal fits of 7 objects, range from 1.02 to 1.48, with a weighted mean obtained of 1.14 ± 0.15 , consistent with the mean value derived from *Spitzer*, 1.20 ± 0.35 (Stansberry et al. 2008). These low η values are compatible with low thermal inertias, presumably due to high porosity of regolith-like surfaces.
- We obtain for the first time the albedo and size of the very large SDO 2007 OR₁₀: $D = 1280 \pm 210$ km, $p_R = 18.5^{+7.6}_{-5.2}\%$. Along with its surface composition, this indicates that the object is Quaoar-like.
- Our size/albedo estimations for the Eris/Dysnomia system ($D = 2454 \pm 117$ km, $p_V = 84.5 \pm 8.8\%$) are compatible within error bars with occultation results by Sicardy et al. (2011), but further analysis is needed.
- We find a significant correlation between albedo and diameter (more reflective objects being bigger), probably due to the fact that large objects can retain bright ices more easily than small objects. Stansberry et al. (2008) obtained a similar result for a larger sample of TNOs, but they noted that the correlation is sensitive to changes in the classification used (i.e. MPC vs. DES; Elliot et al. 2005).
- We also find positive correlations between albedo and perihelion distance, and between diameter and perihelion distance (brighter and bigger objects having larger perihelia). The first correlation has been seen before based on *Spitzer* measurements (Stansberry et al. 2008) and interpreted in terms of increased ice sublimation and/or increased space weathering at low heliocentric distances. It seems more difficult to find a physical explanation for the second correlation.

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Appendix A: Data reduction

In this appendix, we describe the reduction process applied to the PACS data in order to obtain what we call “single” and “combined” maps.

A.1. General PACS photometer data reduction

As explained in the main text (see Sect. 3.1) the data reduction of the maps was performed within HIPE (version 6.0.2044). We modified and adapted the standard HIPE scripts for the needs of our programme. Thus, the PACS photometer data is reduced from Level-0 to Level-2 using a modified version of the standard mini-scanmap pipeline. A major difference of our reduction chain compared with the standard pipeline is the application of frame selection on scan speed rather than on building block identifier (also known as BBID, which is a number that identifies the building block – a consistent part – of an observation). It has been widely tested that the application of the scan speed selection increases the number of useable frames, and finally increases the SNR of the final maps by 10–30% (depending on the PACS observation requests (AOR) setup and on the band used), which is especially important for our faint targets.

Since our targets move slowly (a few $''/h$), and the total observation time per scanning direction in one visit is between 10–25 min we do not correct for the proper motion. Performing this kind of correction would smear the background, and would make it impossible to make a correct background subtraction in the later stages (see Sect. A.2).

We use a two-stage high-pass filtering procedure, as in the standard mini scan-map pipeline. In the first stage a “naive” map is created. This map is used in the second stage to mask the neighborhood of the source and the high flux pixels. In the second stage the vicinity of the source has been masked (2 times the FWHM of the beam of the actual band), as well as all pixels with fluxes above $2.5\times$ the standard deviation of the map flux values. We used the standard high-pass filter width parameters of 15, 20 and 35. The final maps are created by the *PhotProject()* task, using the default dropsize parameter.

These first steps lead to the production of one “single” map per visit, filter, and scan direction (i.e. in total 8 maps per object in the red, and 4 maps in the blue/green created using the *MosaicTask()* in HIPE). The sampling of the single maps generated with these scripts are $1.1''/\text{pixel}$, $1.4''/\text{pixel}$, and $2.1''/\text{pixel}$ for the blue ($70\ \mu\text{m}$), green ($100\ \mu\text{m}$) and red ($160\ \mu\text{m}$) bands respectively.

A.2. Building final maps for photometry

We then use these single maps to generate the final “combined” maps on which the photometry will be performed. Essentially, to generate the combined maps, we determine the background map, subtract it from each single map, and finally co-add all the background-subtracted maps. A detailed description of this process is as follows:

- i) We have initially a set of 8 (red) or 4 (blue and green) single maps taken on different dates. Considering the red maps, let us call t1 to t4 (t5 to t8) the dates corresponding to the first (second) visit. t1-t4 and t5-t8 are separated by typically 1–2 days so that the target motion (typically $30\text{--}50''$ as described in Sect. 2 of the main text) produces a significant change in the observed sky field (see Fig. A.1).

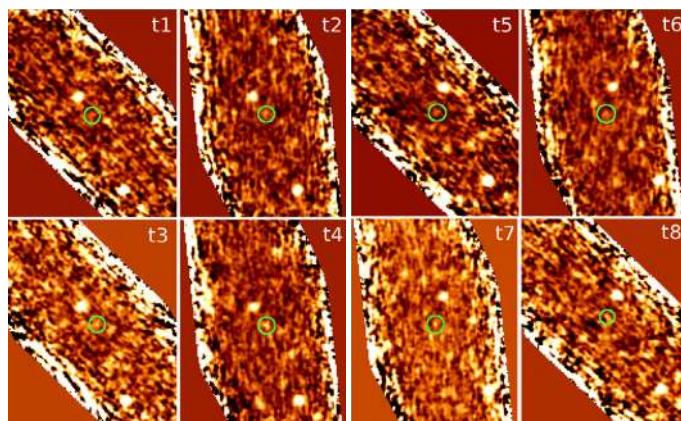


Fig. A.1. Left four panels: Typhon red band 1st visit single maps (t1 to t4). Right four panels: Typhon 2nd visit single maps (t5 to t8). t1, t3, t5, and t8 were observed with a scan angle of 110° , and t2, t4, t6, and t7 with a scan angle of 70° with respect to the detector array. The green circle marks the object position.

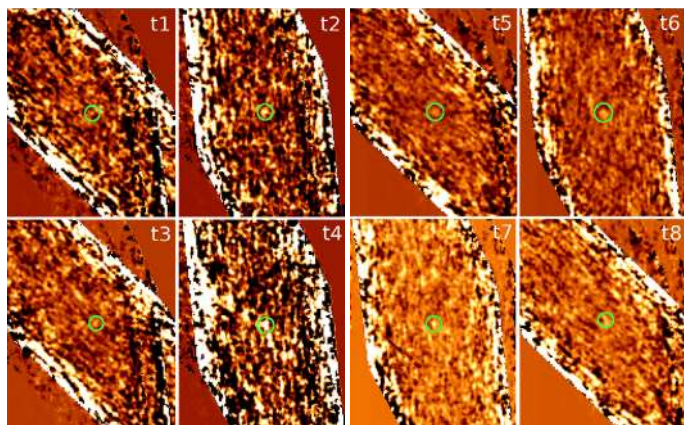


Fig. A.2. Same as Fig. A.1 for the background-subtracted maps.

- ii) A background map is generated using the single maps. To do this we “mask” the target in each of the 8 (4) single maps and co-add the maps in the sky coordinate system. This step produces a background map with high SNR without the target (see the right panel in Fig. A.3 for the Typhon case at $160\ \mu\text{m}$).
- iii) The background map is subtracted from the single maps (Fig. A.1), producing 8 (4) single maps with background removed. We call these images “background-subtracted maps” (Fig. A.2).
- iv) Finally the background-subtracted maps are co-added in the target frame (center panel of Fig. A.3), producing the final combined map on which photometry is performed.

Note that in step ii) before combining the images of the two epochs, we need to calculate the optimal matching offset between the coordinate systems of the two maps since, when we use the original World Coordinate System (WCS) information stored in the file headers, artifacts of bright sources remain in the background subtracted image. The best offset position was found in the following way: we added a small offset – in steps of $0.5''$ in both the RA and Dec directions – to the appropriate original WCS parameters in the file headers, and performed the background subtraction. For each of these maps the standard deviation was calculated for pixels with a coverage value of at least 35% of the maximum coverage of the map. The offset

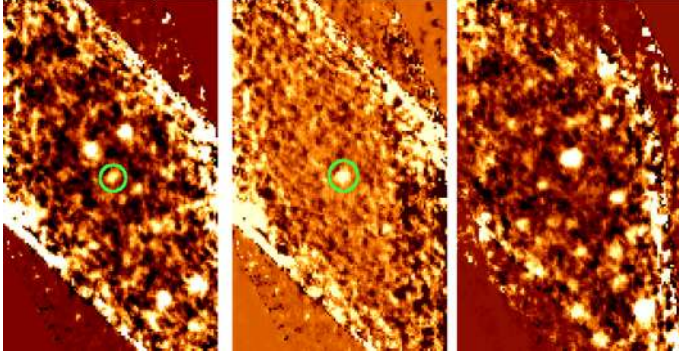


Fig. A.3. *Left:* Typhon simple coadded map in red band. Note that in this case the background is the average (centered in the target) of backgrounds in maps t1-t8 of Fig. A.1, so that the bright background sources appear twice. Green circle marks the object position. *Center:* Typhon background-subtracted coadded map in red band. *Right:* background-subtracted map (target masked).

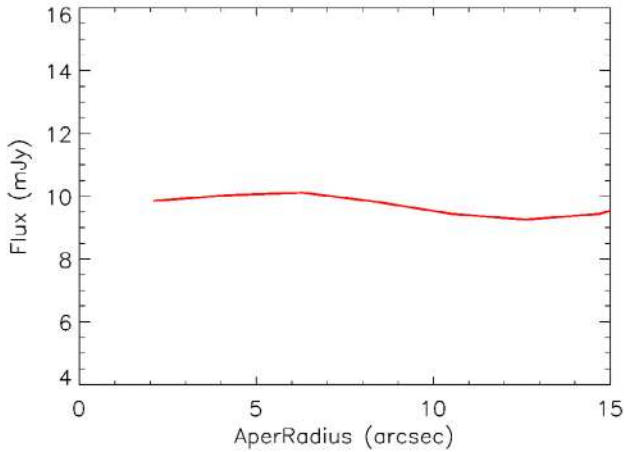


Fig. A.4. Aperture-corrected curve-of-growth obtained from Typhon background-subtracted coadded map in red band (Fig. A.3-center).

values related to the lowest standard deviation correspond to the best matching of the two backgrounds. After this procedure the artifacts of bright sources (e.g. pairs of positive-negative spots) completely disappeared (or, at least, were below detection), and the noise in the background decreased notably. This method was performed on the $160\mu\text{m}$ band measurements, where the effect of the background is the largest. However, it has been checked in a series of measurements that the same offsets can be applied to the 70 and $100\mu\text{m}$ images as well.

An alternate, simpler method, to obtain final maps is to co-add directly the original single maps (i.e. not background-corrected) in the target frame. We call this the simple coaddition method (left panel of Fig. A.3). This method is obviously less optimal than the previous one in terms of SNR, but provides a useful test to demonstrate that the background subtraction is not introducing any spurious effects.

A more detailed description about the whole PACS data reduction process will be published in Kiss et al. (in prep.-a).

Appendix B: Statistical aspects

B.1. “Rescaled error bar” approach

As indicated in the main text (see Sect. 4.3), error bars on the fitted parameters (diameter, albedo and beaming factor) are

determined through a Monte-Carlo approach which essentially consists of randomly building synthetic datasets using uncertainties in the measured fluxes. However, when the measurement errors bars are too small, or similarly when the model is not completely adequate (both cases being indicated by a “poor model fit”), the described Monte-Carlo approach will underestimate the uncertainties on the solution parameters. In this case, we adopted a “rescaled error bar” approach described hereafter.

Quantitatively, the fit quality is determined by the value of the reduced χ^2 :

$$\chi_{\text{red}}^2 = \frac{\chi^2}{\nu} = \frac{1}{\nu} \sum \frac{(O - M)^2}{\sigma^2} \quad (\text{B.1})$$

where O , M and σ are the observed, modelled and error bar flux values, and ν is the degree of freedom ($\nu = N - 1$ for fixed- η , and $\nu = N - 2$ for floating- η , where N is the number of thermal wavelengths available). While $\chi_{\text{red}}^2 \sim 1$ indicates a good fit, $\chi_{\text{red}}^2 \gg 1$ indicates a poor fit. The idea is therefore to empirically “rescale” (uniformly, in the lack of a better choice) all error bars σ by $\sqrt{\chi_{\text{red}}^2}$ before running the Monte-Carlo approach. This method leads to much more realistic error bars on the solution parameters. However, the range of χ_{red}^2 for which this approach is warranted depends on the number of data points, as for few observations χ_{red}^2 does not have to be closely equal to 1 to indicate a good fit. Specifically, the variance of the variance estimator of a distribution of N points picked from a Gaussian distribution with dispersion = 1 is itself a Gaussian with a mean equal to unity and a standard deviation equal to $\sqrt{2/N}$. If we had for example $N = 1000$ observations, 68.2% of the good fits have a reduced χ^2 between 0.955 and 1.045, i.e. χ_{red}^2 is strongly constrained to 1; for $N = 5$ (resp. 3) observations in contrast, this range is much broader, 0.368–1.632 (resp. 0.184–1.816). This means for example that for 3 data points (PACS only), a reduced χ^2 of e.g. 1.6 is acceptable. We considered these N -dependent limits as the thresholds beyond which the fits are statistically bad and the error bars need to be rescaled. Note finally that the rescaling approach is merely an “operative” method to avoid unrealistically low error bars on the fitted diameter, albedo and beaming factor, and that error bars shown in Figs. 1 and 2 of the main text are the original, not rescaled measurement uncertainties.

B.2. Spearman-rank correlation with error bars

As described in the main text the Spearman- ρ correlation test is distribution-free and less sensitive to outliers than most other methods but, like others, treats data-points as “exact” and does not take into account their possible error bars. Any variations in the measured data points within their error bars, may change the correlation coefficient, however. Furthermore, each correlation coefficient has its own confidence interval, which depends on the number of data points and on the magnitude of the correlation. To account for these effects we used the following three procedures:

1. To estimate the most probable correlation coefficient given the error bars, we generate 1000 samples of data points, building each synthetic dataset from its associated probability function. When errors bars are symmetric this probability function is considered to be Gaussian and the error bar correspond to one standard deviation. When errors bars are asymmetric, we fit a lognormal probability function such that the observed value corresponds to the distribution’s mode, and the interval between the upper and lower limits of the

observation corresponds to the shortest interval containing 68.2% of all possible values. The resulting distribution of correlation values is not Gaussian, but its Fisher-transform $z = \operatorname{arctanh}(\rho)$ is. So, we can determine the most probable correlation value, $\langle \rho \rangle$ from our Monte-Carlo simulations, and its upper and lower limits ($+\sigma_{\text{MC}}/-\sigma_{\text{MC}}$), which are not necessarily symmetric after the reconversion using $\rho = \tanh(z)$ (see Peixinho et al. 2004, for more details). It is noticeable (and expected) that observational error bars “degrade” the correlation. The approximate significance p -value, or confidence level (CL), of ρ can be computed from $t = \rho \sqrt{(n-2)/(1-\rho^2)}$, which follows a t-Student distribution with $n-2$ degrees of freedom. However, when $n \lesssim 15$, using t provides a slight overestimation of the significance. We have compared the previous calculation of the significance with exact values tabulated by Ramsey (1989) and computed adjustments required to obtain a more accurate approximation of the ρ 's and p -values in the case of low n .

2. The confidence level of a given ρ results from testing the hypothesis “the sample is correlated” against the hypothesis “the sample correlation is zero”. Knowing the confidence

interval (CI) within which the correlation ρ value of the parent population lies may be more informative. For example, suppose we have $\rho = 0.7$ with a 3σ confidence level; we would conclude that the sample is correlated. But if the 68% confidence interval of the correlation were say $[0.3, 0.9]$, we would be unsure if the correlation was very strong or rather weak. To estimate the shortest ($+\sigma_B/-\sigma_B$) interval containing 68.2% of the population's ρ (i.e. the equivalent to the Gaussian 1σ interval), we used 1000 bootstrap extractions from the data-sample computing this range as we did for the previous item (e.g. Efron & Tibshirani 1993).

3. Finally, to be fully correct, one should perform the 1000 bootstraps on each one of our 1000 Monte-Carlo simulations to obtain the true 68% confidence interval of $\langle \rho \rangle$, a computationnally heavy task. Fortunately, the combination of the two effects can be obtained by quadratically adding the standard deviations of the Gaussian distributions of the Fisher-transform of the Monte-Carlo simulations and the bootstraps, i.e. $\sqrt{\sigma_{\text{MC}}^2 + \sigma_B^2}$, which, after reconversion to ρ , will give our final best estimate for the 68% confidence interval noted as $\langle \rho \rangle_{-\sigma}^{+\sigma}$.