Surface properties of extreme TNOs based on Herschel/PACS measurements: Sedna and 2010 EK_{139}

"TNOs are Cool!": A survey of the trans-Neptunian region

András Pál, Csaba Kiss, Thomas G. Müller and the "TNOs are Cool!" team.

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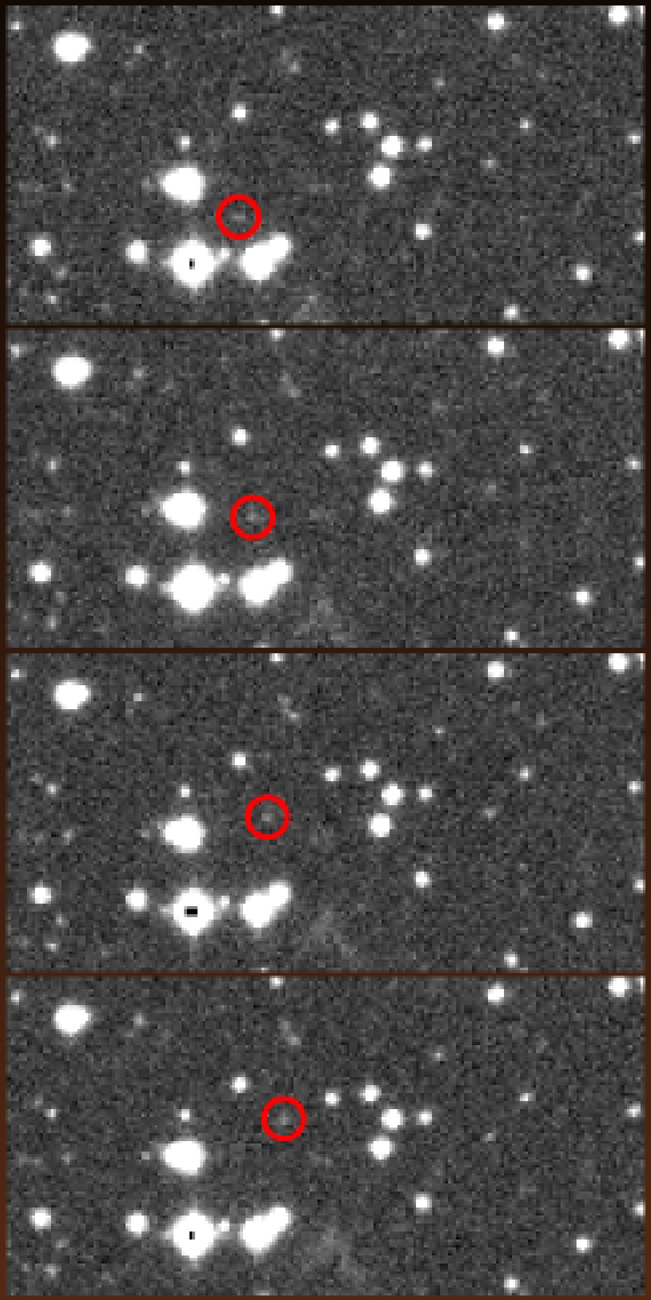
The "TNOs are cool!" program

About this program:

- Open Time Key Programme: "TNOs are Cool!" (Th. Müller et al. 2009)
- $\approx$400 hours of observing time with the Herschel Space Observatory
- $\approx$130 objects, representing various dynamical classes of the trans-Neptunian population.
- Instruments: mostly PACS (between 50 – 200 μm), some targets with SPIRE (200 – 600 μm).
- Goals: accurate estimation of diameters, albedos, constraints on the surface properties, searching for correlations between various physical parameters. Also: observations of thermal light curves.
- Typical temperatures at this regime of the Solar 30 –50 K $\Rightarrow$ peaking at the PACS bands.

The Herschel Space Observatory



Left: the Herschel Space Observatory before launching. Right: the Herschel Space Observatory orbiting the 2^{nd} Lagrangian point of the Sun – Earth system.

(90377) Sedna

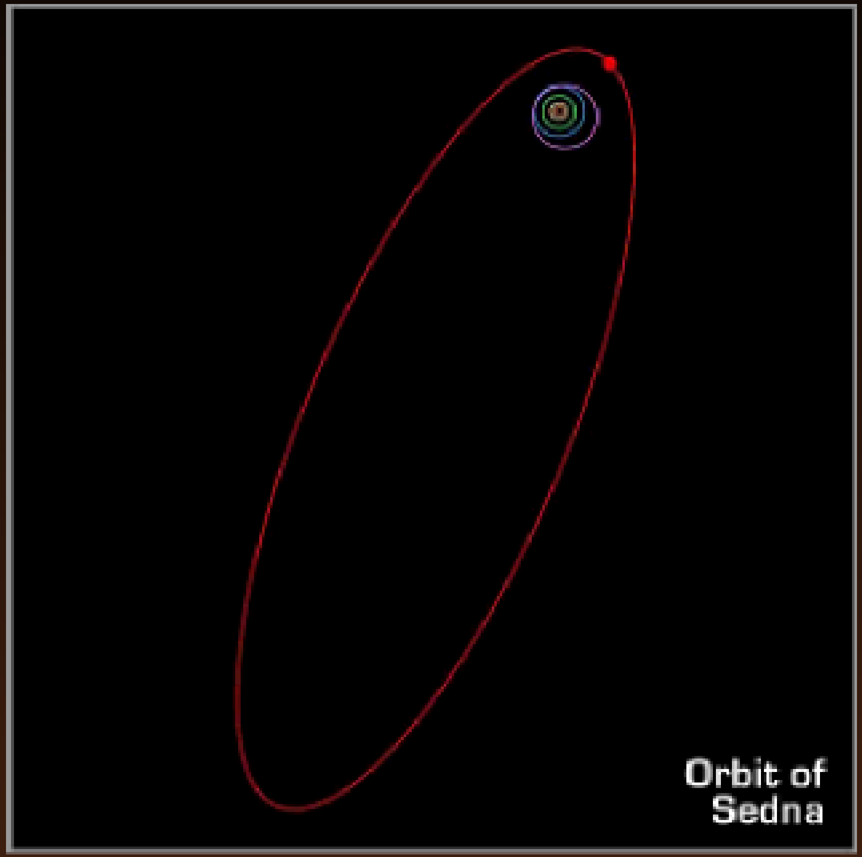
What do we know about (90377) Sedna?

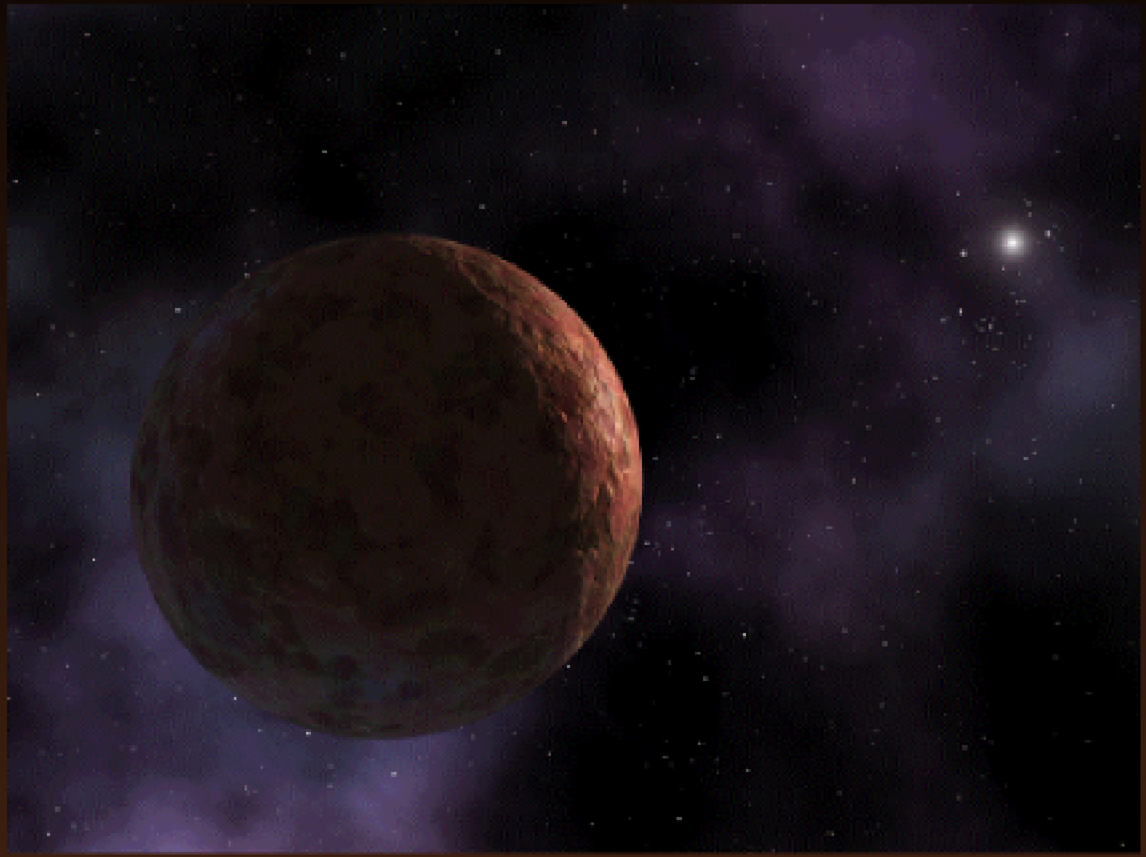
- Orbital elements: known with a sufficient precision, good astrometric observations are available – it is a relatively bright object. This is the first suspected member of the inner Oort cloud (see also 2012 DR_{30}).
- Photometry: extremely red: $V - R = 0.78$ (see also: the color index of the Sun is $V - R = 0.36$).
- Photometric variations: 0.02 mags (peak-to-peak), suspected rotational period: 10.3 hours.
- Spectroscopy: surface similar to many other TNOs and to Triton (methane ice, nitrogen ice, methanol, tholin, water ice)

What we don't know about Sedna:

- Basic physical parameters: size, mass (however: there were former upper limits to the size, see also Stansberry et al. 2008).
- Surface albedo (only lower limit is known).

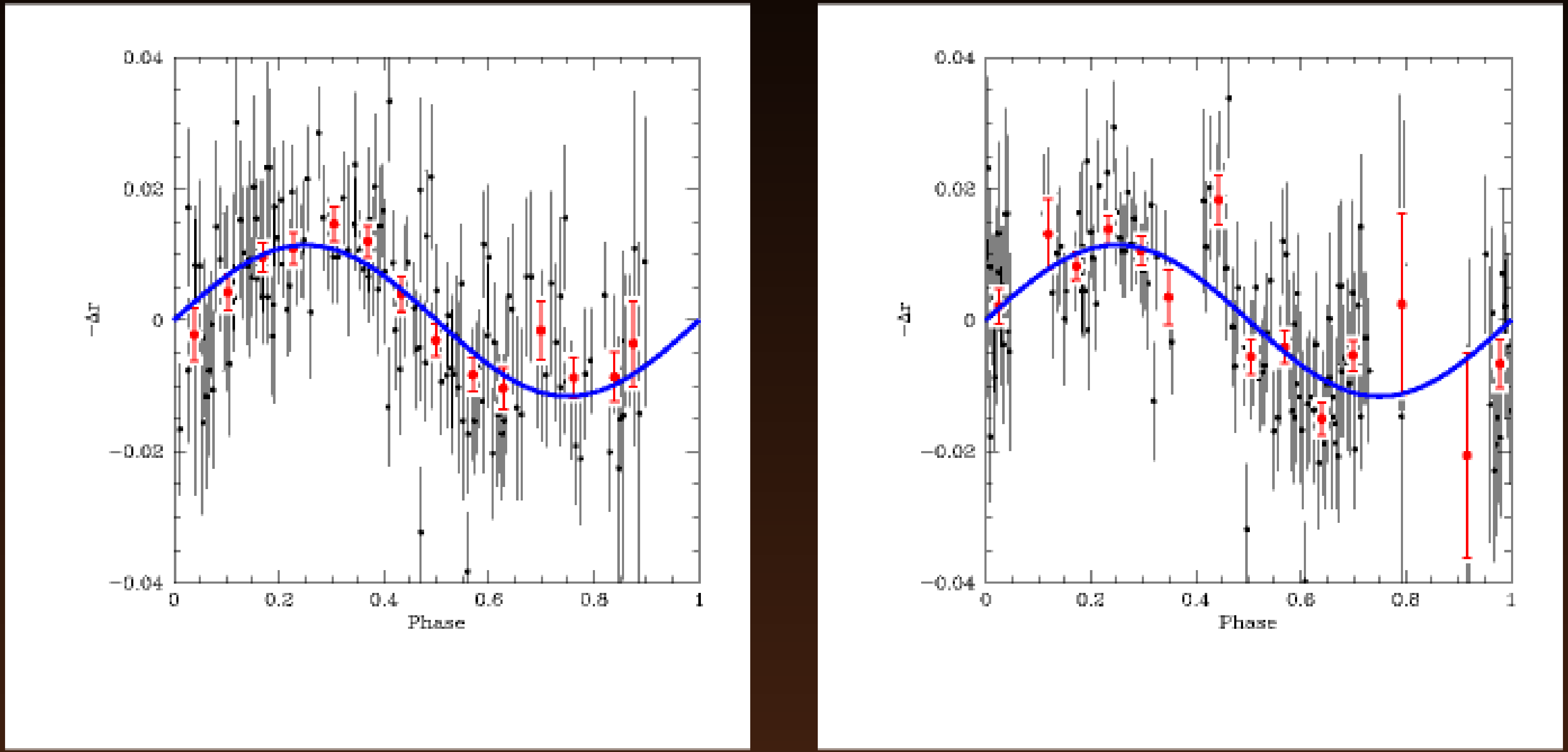
(90377) Sedna





Left: the orbit of Sedna, shown to scale. Right: artist's impression of Sedna.

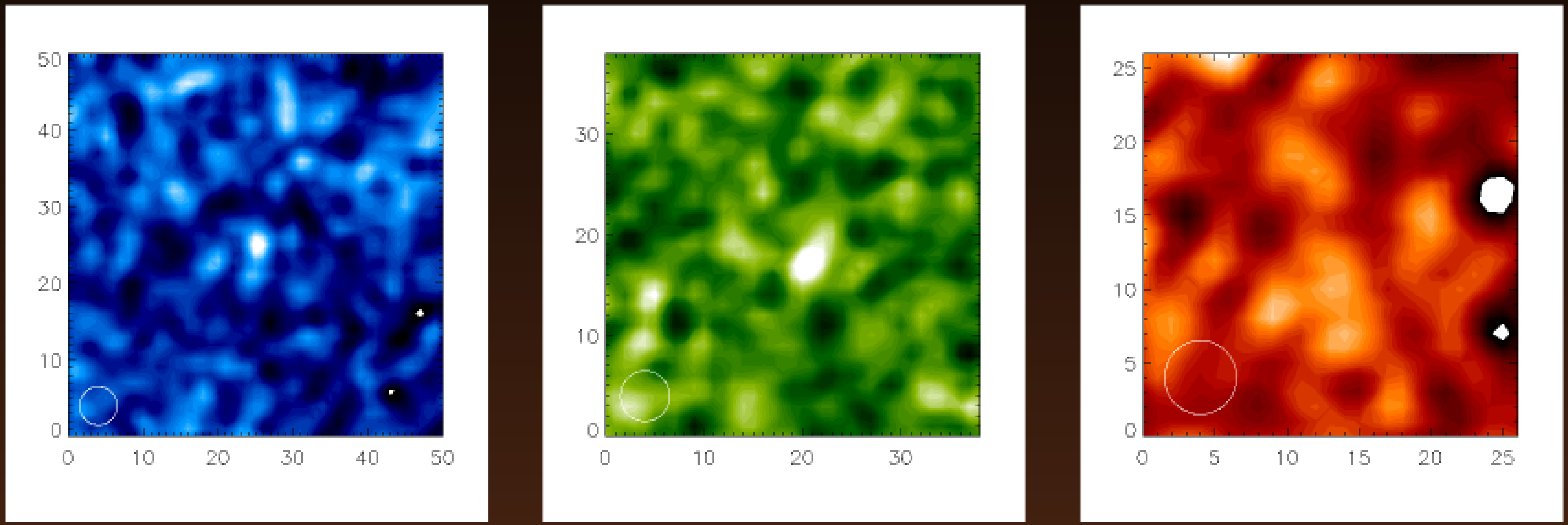
(90377) Sedna



The rotational light curve of Sedna. Left panel: folded with a period of $P = 10.273 \pm 0.002$ *hours. Right panel: folded with a period of* $P = 17.991 \pm 0.006$ *hours. Although the* χ^2 *values are roughly the same for the two fits, the systematic errors are definitely larger in the second case (see also the scatters of the binned data points). Thus, the real rotation period is much likely to be 10.3 hours (see also Gaudi et al. 2005).*

(90377) Sedna

Thermal radiation – our Herschel/PACS measurements:



Combined maps based on Herschel/PACS data. Due to the applied post-processing steps, the only source on these maps is Sedna. From left to right: blue, green and red PACS bands (centered at 70, 100 and 160 microns). These maps show an area of $56'' \times 56''$.

(90377) Sedna

Input parameters of the thermal modelling:

Band	λ	Flux
B	$70\,\mu\mathrm{m}$	$1.8 \pm 0.7\,\mathrm{mJy}$
G	$100\,\mu\mathrm{m}$	$4.2 \pm 0.9\,\mathrm{mJy}$
R	$160\,\mu\mathrm{m}$	$2.7 \pm 1.3\,\mathrm{mJy}$

Quantity	Value
r	$87.43\,\mathrm{AU}$
Δ	$87.56\,\mathrm{AU}$
α	$0.^{\circ}7$
H_{V}	$+1.83 \pm 0.05$

Source of these data:

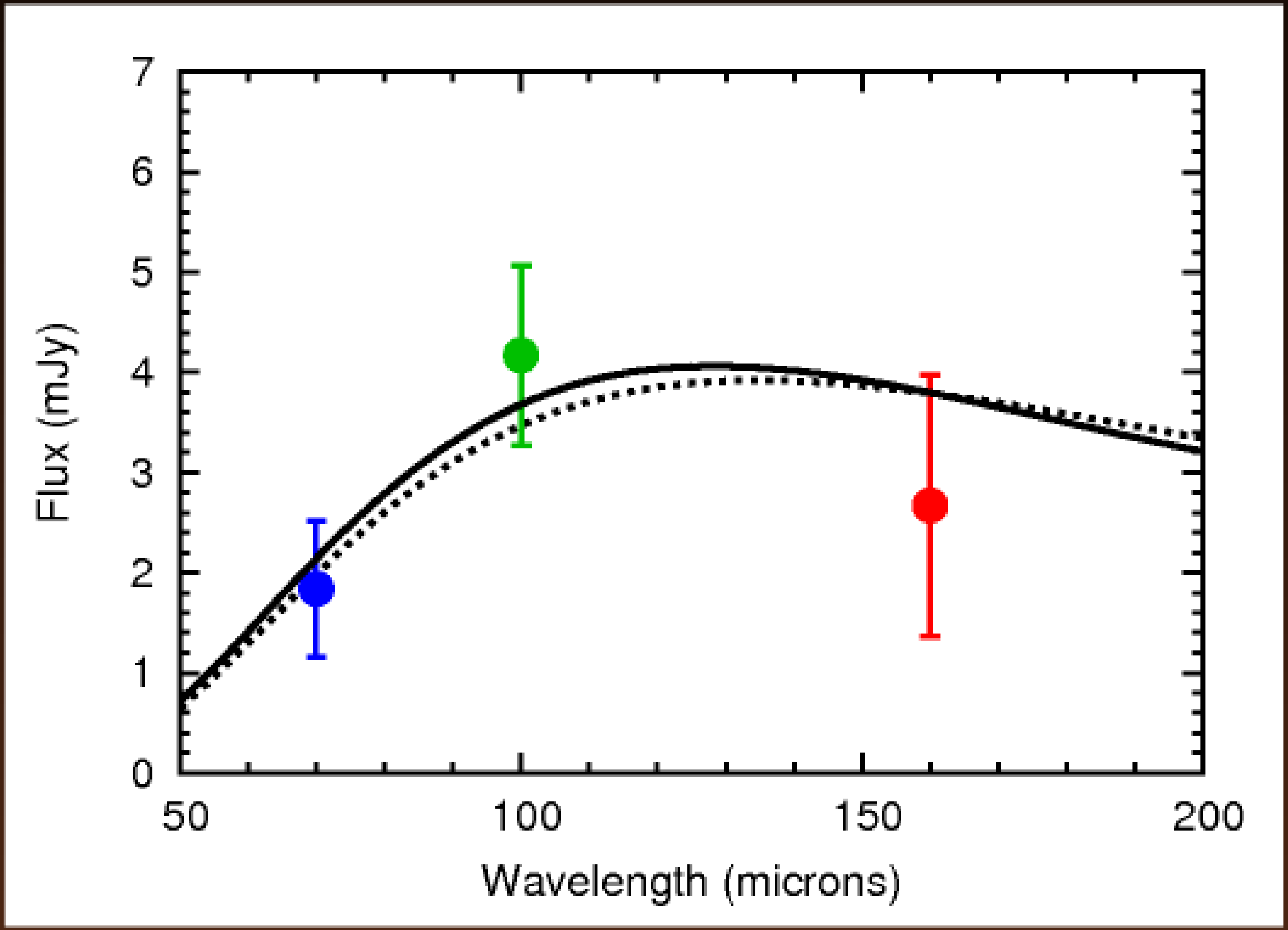
- Our Herschel/PACS measurements;
- MPC and/or Horizons ephemerides;
- Data from the literature (esp. Rabinowitz, Schaefer & Tourtellotte, 2007)

Modelling:

- combination of optical and infrared data
- uncertainties are estimated via Monte Carlo.

(90377) Sedna

Modelling of the thermal fluxes:



Applied models: TPM (Thermophysical Model, Lagerros 1996, 1997, 1998, thick line), STM (Standard Thermal Model with floating beaming parameter, Lebofsky et al. 1986, dashed line). NEATM (Harris, 1998, just checked)

(90377) Sedna

Results of the thermal modelling – STM:

- diameter: $D = 990 \pm 95\,\mathrm{km}$,
- geometric albedo: $p_V = 0.34 \pm 0.07$.

Results of the thermal modelling – TPM:

- diameter: $D = 995 \pm 80\,\mathrm{km}$,
- geometric albedo: $p_V = 0.32 \pm 0.06$.

The results of the two modelling agree well.

2010 EK_{139}

What do we know about 2010 EK_{139}?

- Orbital elements: not so precise. Recent discovery, (Sheppard et al. 2011), although it was identified on Palomar plates from 2002. However, it is relatively bright (20 mags).
- A suspected resonance 2:7(?), see also: 2006 HX_{122}.

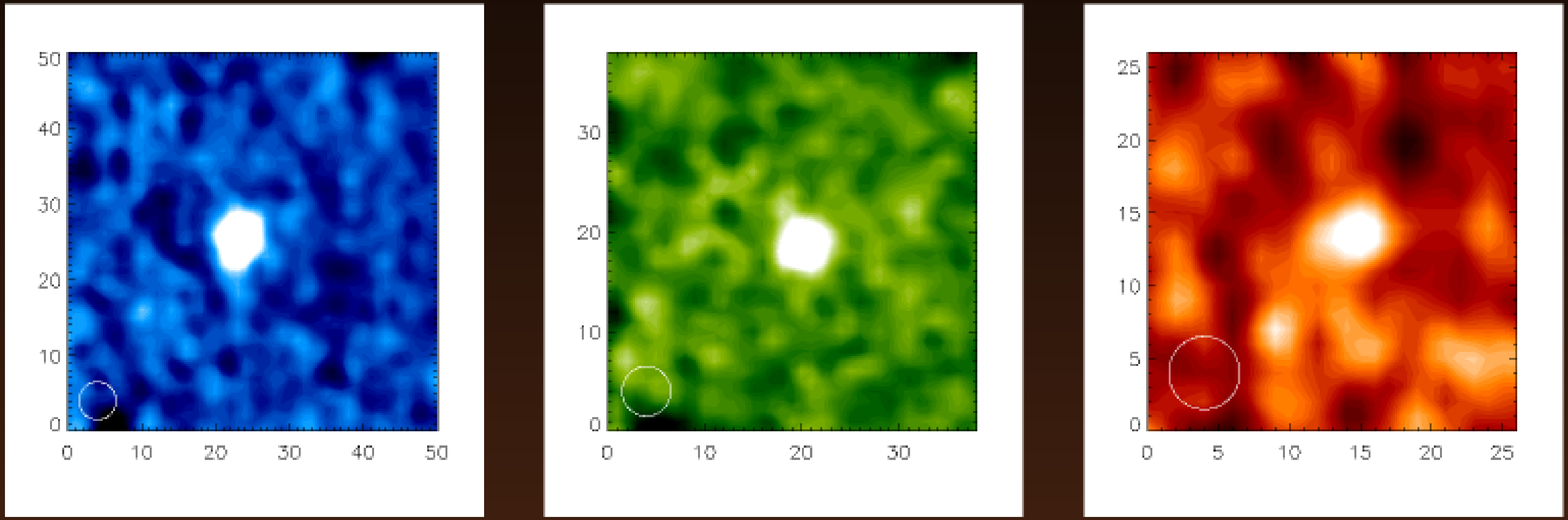
What we don't know about 2010 EK_{139}:

- Photometry: unknown color.
- Photometric light variations: it is also not known, however, it cannot be ruled out as well. Thus, we don't know anything about the rotation.
- Basic physical parameters: size, mass.
- Surface albedo.

Why is it interesting?

2010 EK_{139}

Thermal radiation – our Herschel/PACS measurements:



Combined maps based on Herschel/PACS data. Due to the applied post-processing steps, the only source on these maps is 2010 EK_{139}. From left to right: blue, green and red PACS bands (centered at 70, 100 and 160 microns). These maps show an area of $56'' \times 56''$.

2010 EK_{139}

Input parameters of the thermal modelling:

Band	λ	Flux
B	$70\,\mu m$	$17.4 \pm 1.1\,mJy$
G	$100\,\mu m$	$16.3 \pm 1.4\,mJy$
R	$160\,\mu m$	$11.9 \pm 1.8\,mJy$

Quantity	Value
r	$39.08\,AU$
Δ	$39.50\,AU$
α	$1\overset{\circ}{.}3$
H_V	$+3.80 \pm 0.10$

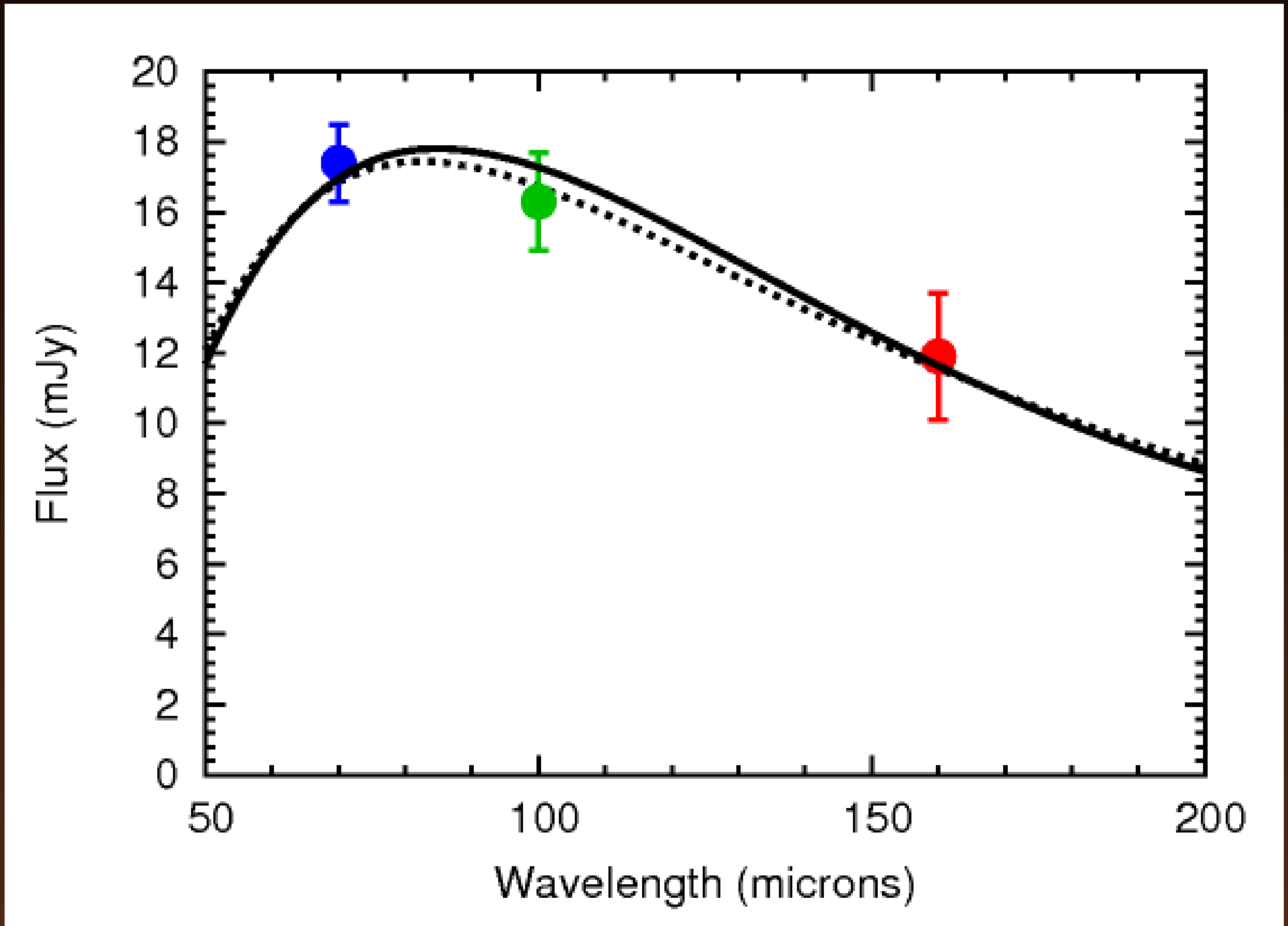
Source of these data:

- Our Herschel/PACS measurements;
- MPC and/or Horizons ephemerides;
- MPC and data from the literature (Sheppard et al. 2011), conservative error estimations. Are there any systematics in the MPC data?

Modelling: similar to the case of Sedna.

2010 EK_{139}

Modelling of the thermal fluxes:



Applied models: TPM (Thermophysical Model, Lagerros 1996, 1997, 1998, thick line), STM (Standard Thermal Model with floating beaming parameter, Lebofsky et al. 1986, dashed line). NEATM (Harris, 1998, just checked)

2010 EK_{139}

Results of the thermal modelling – STM:

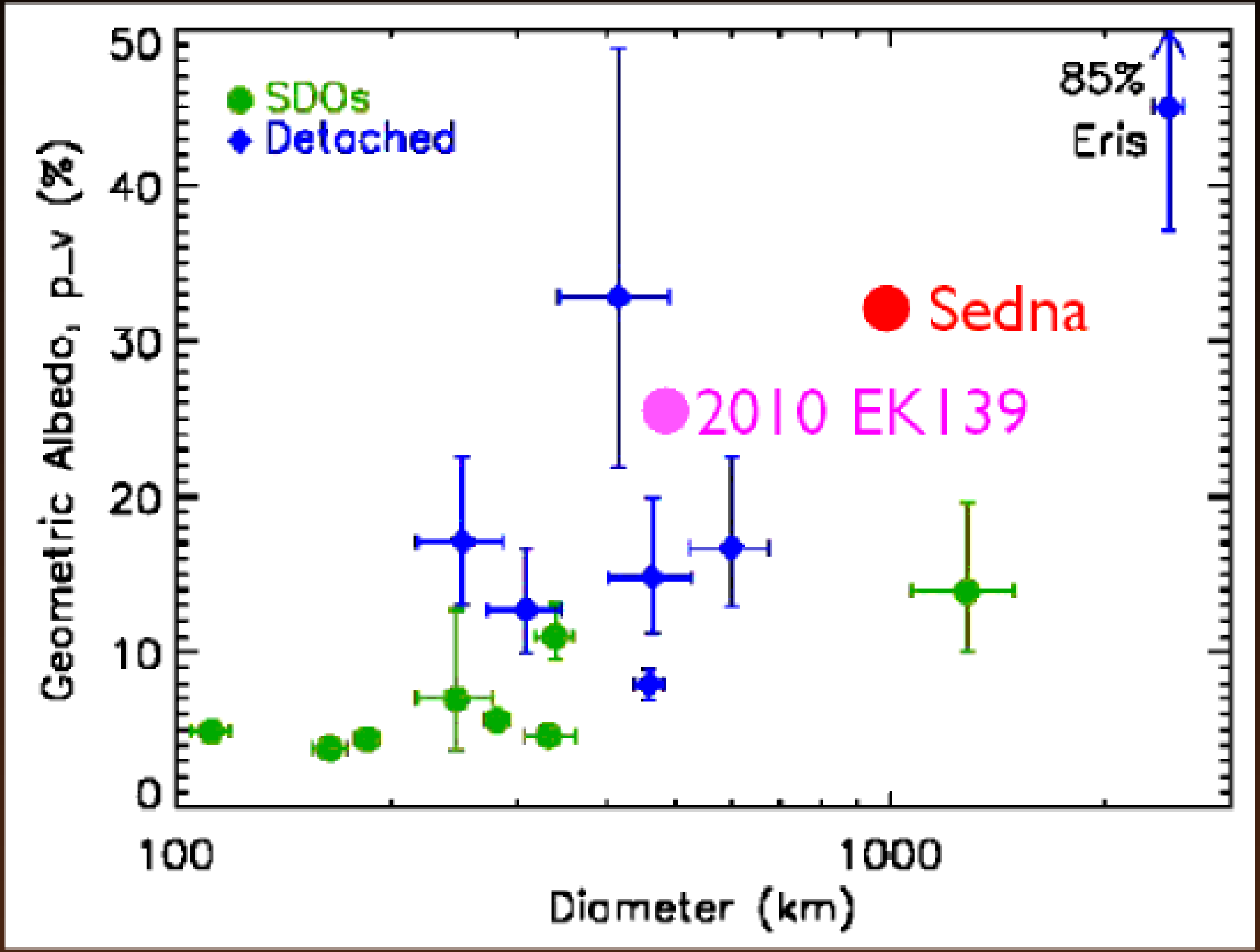
- diameter: $D = 450 \pm 35\,\mathrm{km}$,
- geometric albedo: $p_V = 0.26 \pm 0.05$.

Results of the thermal modelling – TPM:

- diameter: $D = 470^{+35}_{-10}\,\mathrm{km}$,
- geometric albedo: $p_V = 0.25^{+0.02}_{-0.05}$.

The results of the two modelling agree well.

Sedna & 2010 EK_{139}



The suspected correlation between the diameter and geometric albedo of scattered disk and/or detached objects (Santos-Sanz et al. 2012). Data for Sedna and 2010 EK_{139} confirms this correlation.

Sedna & 2010 EK_{139}

Interpretation of our data and modelling – Sedna:

- It is far <u>and</u> does not come inside the Solar System ($q \approx 76\,\mathrm{AU}$): volatiles (methane, nitrogen, carbon-monoxide) are frozen to the surface.
- Large size: these materials are even retained after sublimation.
- Therefore, the higher surface albedo is not so surprising.

Interpretation of our data and modelling – 2010 EK_{139}:

- It is not so far away <u>and</u> has a smaller perihelion distance ($q \approx 32.5\,\mathrm{AU}$) <u>and</u> it has a smaller size: volatiles cannot be retained on the surface.
- However: water ice can also be presented on the surface (see other examples, e.g. Haumea: Barkume et al., 2006; Dumas et al. 2011)
- The presence of water ice yields a bluish color (see Brown, 2008), thus water ice might be confirmed by the color index ($V - R \lesssim 0.40$).

Although both objects confirm the correlation between the albedos and diameters of scattered of detached objects, the physics behind these observations are due to different mechanisms. Further observations: 2010 JJ_{124}, 2012 DR_{30}.

Thank you