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

III. Thermophysical properties of 90482 Orcus and 136472 Makemake*

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ABSTRACT

Context. The goal of the Herschel open time programme “TNOs are Cool!” is to derive the physical and thermal properties for a large sample of Centaurs, and trans-Neptunian objects (TNOs), including resonant, classical, detached and scattered disk objects.

Aims. Based on observations of two targets we tried (i) to optimise the SPIRE observing technique for faint (close to the background confusion noise), slowly moving targets; (ii) to test different thermal model techniques; (iii) to determine radiometric diameter and albedo values; (iv) to compare with Spitzer results whenever possible.

Methods. We obtained SPIRE photometry on two targets and PACS photometry on one of the targets.

Results. We present results for the two targets, (90482) Orcus and (136472) Makemake, observed with SPIRE and for one of those targets, Makemake, observed with PACS. We adopt $p_V = 0.27$ and $D = 850$ km as our best estimate of the albedo and diameter of Orcus using single terrain models. Two-terrain models for Makemake, the bright terrain is fitted by $0.78 < p_V < 0.90$, and the dark terrain $0.02 < p_V < 0.12$, giving $1360 < D < 1480$ km.

Conclusions. A single terrain model was derived for Orcus through the SPIRE photometry combined with MIPS data. The Makemake data from MIPS, PACS and SPIRE combined are not compatible with a single terrain model, but can be modelled with a two-terrain fit. These science demonstration observations have shown that the scanning technique, which allows us to judge the influence of background structures, has proved to be a good basis for this key programme.

Key words. techniques: photometric – Kuiper belt objects: individual: 90482 Orcus – Kuiper belt objects: individual: 136472 Makemake – infrared: general – submillimeter: general

1. Introduction

The objects (136472) Makemake (formerly 2005 FY9) and (90482) Orcus (formerly 2004 DW) are among the largest trans-Neptunian objects (TNOs), including resonant, classical, detached and scattered disk objects. Orcus has a diameter near 1000 km (Stansberry et al. 2008), and is one of the few binary TNOs in an orbit resonant with that of Neptune. Near-infrared spectroscopy indicates a surface composed of significant amounts of water ice (e.g. Barucci et al. 2008), as well as ammonia or an ammonia compound. A binary TNO with a known size, Orcus is also known to have a density, $1.5 \pm 0.3 \text{g/cm}^3$, which is intermediate between those of the small TNOs (which are typically $\leq 1$), and the largest objects such as Pluto and Earth, with densities $\geq 2$.

Makemake is particularly interesting because of its exceptionally strong absorption bands from methane ice on its surface (the bands are much stronger than those seen on any other icy solar system object, including Pluto) (e.g. Brown et al. 2007; Eluszkiewicz et al. 2007). The most abundant volatile on Pluto and Triton is nitrogen; while the intrinsically very weak absorption features of nitrogen have not been observed on Makemake, its presence is suggested by the shift in the wavelength of the methane ice bands (Tegler et al. 2008). Spitzer thermal data for Makemake (Stansberry et al. 2008) were also intriguing, showing not only that it is exceptionally large (with a diameter near 1500 km), but that the surface is probably segregated into high- and low-albedo terrains. Here we report our new Herschel (Pilbratt et al. 2010) SPIRE (Griffin et al. 2010) photometry of Orcus and Makemake, and Herschel PACS (Poglitsch et al. 2010) photometry of Makemake. We combine the results with those obtained from the earlier Spitzer data for these objects to form a more complete and accurate picture of their physical characteristics. Our Herschel TNO key programme (Müller et al. 2009) seeks to determine the properties of 139 TNOs mainly using the Herschel PACS instrument via photometry at 70, 100 and 160 $\mu$m. For the 15 brightest objects the programme will also obtain SPIRE photometry at 250, 350 and 500 $\mu$m. Orcus and Makemake were observed as part of the Herschel science demonstration phase sub-programme, which was aimed at validating the scientific usability and performance of the Herschel instrument observing modes. This programme included observations of 17 of our targets, PACS measurements of 7 of these targets are discussed in Paper I (Müller et al. 2010) and the lightcurve of 136108 Haumea is discussed in Paper II (Lellouch et al. 2010).

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2. Observations

For the purposes of planning this programme, model fluxes using typical values (geometric albedo \(p_v = 0.08\), beaming factor \(\eta = 1.25\)) were generated based on estimates inherited from Spitzer results (Stansberry et al. 2008). This led to predictions of SPIRE 250 μm fluxes of 16 and 35 mJy for 90482 Orcus and 136472 Makemake respectively for the 2009 November/December time period.

When using Herschel observers must select an observing mode from a small number of astronomical observation templates (AOTs). For SPIRE the pre-flight prediction for extra-galactic confusion limit was expected to be in the region of 7 mJy rms for each band (Griffin et al. 2008). Because the predicted TNO fluxes were close to these values, the chop/nod point source mode would not have produced accurate measurements of the TNO fluxes, as both additional noise, close to the galactic confusion limit was expected to be in the region of 7 mJy rms for each band (Griffin et al. 2008).

Notes. r: Sun-target distance, Δ: Herschel-target distance, α: phase angle, \(H_v\) magnitudes, lightcurve \(\Delta_{mag}\), and the rotation period [hours], references are given for the last three columns.

References. (1) Thirouin et al. (2010); (2) Heinze & de Lahunta (2009); (3) Ortiz et al. (2006).
varying $\eta$; $\eta < 1$ corresponds to low conductivity surfaces that are rough, while $\eta > 1$ corresponds to relatively high conductivity surfaces, which are smoother. These effects can be modelled in detail with a more complicated thermophysical model (see below), but if the goal of the modelling is merely to determine the albedo and diameter ($D$) of an object, the NEATM gives excellent results (Harris et al. 1998).

Uncertainties in the NEATM fit parameters were determined from a Monte-Carlo analysis. To this end, 300 sets of normally distributed flux values were generated with a random-number generator; for each wavelength, the mean of the random distribution equals the measured value, and the standard distribution equals the measured flux uncertainty. The NEATM was fitted to each of those 300 flux sets, then we determined the mean and standard distribution of each fit parameter, taken to be the overall best-fit value and its statistical uncertainty. The results are $p_V = 0.25 \pm 0.03$, $D(km) = 867 \pm 57$, $\eta = 0.97 \pm 0.07$. This $\eta$ value is slightly lower than the average $\eta$ for KBOs (1.3 $\pm$ 0.4, from data in Stansberry et al. 2008), but it is consistent with the observed range. This suggests that Orcus probably has a slightly lower thermal inertia and/or rougher surface than “typical” KBOs, although this is not a very significant difference.

A thermophysical model (TPM, Lagerros 1996, 1997, 1998; Müller & Lagerros 1998) was also used to obtain radiometric properties. The TPM we used for Orcus assumes a spherical body, with the rotation period given in Table 1, and the rotation axis perpendicular to the ecliptic. The “free” parameter is the thermal inertia, $\Gamma = \sqrt{\rho k c}$, where $k$ is the conductivity, $\rho$ is the mass density, and $c$ is the heat capacity per unit mass of the surface materials. Surfaces with high values of $\Gamma$ tend to change temperature slowly, while those with low values of $\Gamma$ (which are assumed in the NEATM/STM) approach instantaneous equilibrium with the insolation striking them.

Based on the two Spitzer-MIPS bands and two Herschel-SPIRE bands we found the best match between all observation for a very low thermal inertia below $3 \, \text{J m}^{-2} \, \text{s}^{-0.5} \, \text{K}^{-1}$. The corresponding radiometric effective diameter is $D_{\text{eff}} = 829^{+119}_{-43}$ km and a geometric albedo of $p_V = 0.28^{+0.04}_{-0.06}$. The solution with the full albedo and diameter range is shown in Fig. 1.

Taking both the NEATM and TPM results into account, we adopt $p_V = 0.27^{+0.05}_{-0.03}$ and $D = 850 \pm 90$ km as our best estimate of the albedo and diameter of Orcus. The quoted uncertainties span the range of results from these two quite different modelling approaches, and are consistent with the accuracy we expect based on previous experience for radiometric results, namely that $D$ can be determined to no better than 10%, and $p_V$ to no better than 20%. These uncertainties also bound those introduced by uncertainties in Orcus’ absolute magnitude and lightcurve variations, although the influence of the lightcurve variation is minor, because $\Delta_{\text{mag}}$ of 0.04/+-0.01 indicates that Orcus’ shape is very close to a sphere and even a variation of 0.1 mag in $H_V$ would lead to a diameter change of only 4–5% (and a change in geometric albedo of 8–10%). These values are also consistent with the $D(km) = 940 \pm 70$ and $p_V = 0.28 \pm 0.04$ found by Brown et al. (2010) using the Spitzer data only.

### 3.2. Makemake

As noted by Stansberry et al. (2008), Makemake is too bright at 24 micron wavelengths to allow any simple thermal model to fit the spectral energy distribution (SED). This is still the case with our new Herschel data. As an example, we show a TPM fit to the Herschel and Spitzer data from 70–500 $\mu$m in Fig. 2. For a range of assumptions about the spin vector, TPM models with fit to these wavelengths give $1350 < D < 1510$ km, and albedos $0.7 < p_V < 0.9$. The model vastly under-predicts the 24 micron flux, which made us explore enhanced models.

A slightly more complex model, consisting of high-albedo and low-albedo terrains, is capable of fitting the entire SED. The surface of Makemake has large amounts of methane ice, which is volatile even at temperatures found at 52 AU from the Sun. Taking Pluto and Triton as guidance, it should be expected that the methane ice will form extensive high-albedo terrains. Additionally, the methane will sublime in areas of high-insolation, forming new deposits in darker areas. This volatile transport should expose underlying non-volatile materials (such as water ice and organics derived by photolysis from the methane). The presence of organics should cause the substrate albedo to be quite low, perhaps as dark as cometary nuclei.

Figure 2 shows an example of a two-terrain model fit to all the data. The two-terrain fit not only passes through the 24 micron Spitzer point, but also provides an improved fit at the PACS and SPIRE wavelengths. The family of two-terrain models that produce reasonable fits provide the following constraints. 1) For the bright terrain, $0.78 < p_V < 0.90$, and the effective radius is $660 < R_{\text{eff}} < 715$ km. 2) For the dark terrain $0.02 < p_V < 0.12$, and its extent is given by $155 < R_{\text{eff}} < 190$ km. Here $R_{\text{eff}}$ is the radius of an object with the equivalent projected area as the terrain in question. Cast in another way, the dark terrain is

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**Table 3. Source fluxes obtained from SPIRE and PACS photometry plus previously derived MIPS fluxes.**

<table>
<thead>
<tr>
<th>Target</th>
<th>Instrument</th>
<th>$\lambda_{eff}$</th>
<th>FD [mJy]</th>
<th>Error [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Makemake</td>
<td>MIPS</td>
<td>24</td>
<td>0.30</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>MIPS</td>
<td>71</td>
<td>14.6</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>PACS</td>
<td>70</td>
<td>11.4</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>PACS</td>
<td>100</td>
<td>12.0</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>PACS</td>
<td>160</td>
<td>16.7</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>SPIRE</td>
<td>250</td>
<td>9.5</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>SPIRE</td>
<td>350</td>
<td>7.1</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>SPIRE</td>
<td>500</td>
<td>&lt;8.8</td>
<td></td>
</tr>
<tr>
<td>Orcus</td>
<td>MIPS</td>
<td>24</td>
<td>0.33</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>MIPS</td>
<td>71</td>
<td>26.6</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>SPIRE</td>
<td>250</td>
<td>12.3</td>
<td>2.3</td>
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<tr>
<td></td>
<td>SPIRE</td>
<td>350</td>
<td>6.6</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>SPIRE</td>
<td>500</td>
<td>&lt;10.7</td>
<td></td>
</tr>
</tbody>
</table>
ric albedos for Makemake, but there is indirect evidence (Tegler et al. 2008) that some hot spots may exist. Methane has too low a vapor pressure for this to occur primarily at low latitudes, resulting in a nearly isothermal surface (where the volatile ices are sublimed). This is consistent with the TPM fit to the Herschel data. The range of diameters for Makemake corresponding to these radii is $1360 < D < 1480$ km, consistent with the values given above based on the TPM fit to just the long-wavelength data.

The two-terrain models used a beaming parameter for the bright terrain of $1.3 \leq \eta \leq 2.2$. The value of 1.3 is the average for TNOs, and if we assume $\eta < 1.3$ the models produce geometric albedos for Makemake $>1$. While these high albedos are not very likely at high latitudes, they are still consistent with the measured values for $\eta > 1.3$. An $\eta$ value as high as 2.2 is near the upper limit expected based on comparing thermophysical models, and mimics a surface with very high thermal inertia, which makes it a reasonable upper bound for our modeling. Transport (and the accompanying transport of latent heat) can result in high values for thermal conductivity (if the transport occurs between layers in the surface), increasing the apparent thermal inertia. Transport can also occur laterally. In cases where a thick enough atmosphere is present (e.g. Triton and Pluto) the transport of latent heat is comparable to conduction and re-radiation terms, resulting in a nearly isothermal surface (where the volatile ices exist). Methane has too low a vapor pressure for this to occur on Makemake, but there is indirect evidence (Tegler et al. 2008) that it can be transported to the near-IR spectrum for the presence of nitrogen. With its higher vapor pressure, nitrogen could greatly affect the temperature distribution of the high-albedo terrain.

The beaming parameter for the dark terrain is required to be quite low, in the range 0.4–0.5. These low values may require some enhancement to the normal mechanisms thought to result in “beaming”. One possibility is that sunlight, scattered through and/or off nearby raised, high-albedo regions results in enhanced heating of the dark terrains. To be effective, this mechanism would require the dark regions to be comparable in size to the depth of the methane ice surrounding them. The low-amplitude visible lightcurve is not violated in this paradigm, because the dark spots would be small and probably rather evenly distributed. If the dark terrain intrinsically has such an extreme beaming parameter, it could also be distributed as a band at a constant latitude, or as a polar spot, while still being consistent with the observed lightcurve. Another possibility is that the dark terrain is actually an as-yet undiscovered satellite of Makemake. The components of most TNO binaries have very similar colours (and probably albedos), so this is not likely for a small satellite orbiting a methane-rich object such as Makemake.

4. Conclusions

The addition of *Herschel* photometry to the *Spitzer* photometry has extended the thermal SED to 350 $\mu$m and gave improved constraints for modelling. For Orcus the additional SPIRE data allowed a single well constrained model to be fitted, which shows good consistency between the *Spitzer* data and the *Herschel* data. Difficulties in fitting Makemake with a single-terrain model (suspected based on the *Spitzer* data alone) are not diminished by the new PACS and SPIRE data and a two-terrain thermal model, consisting of a limited, low-albedo terrain and an extensive, high-albedo terrain, appears to be required in order to fit the full emission spectrum. The detections were close to the instrumental limit and the measured errors are consistent with the expected instrumental noise (1.8, 1.5 and 2.2 mJy at 250, 350 and 500 $\mu$m, Griffin et al. 2010), demonstrating that SPIRE performs consistently well down to the very weakest sources it will detect. Therefore these observations have demonstrated SPIRE instrument capability and have shown that this observing strategy is the correct choice for the TNO key programme.

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