LETTERS

The trans-neptunian object UB_{313} is larger than Pluto

F. Bertoldi[1,2], W. Altenhoff[2], A. Weiss[2], K.M. Menten[2] & C. Thum[3]

The most distant known object in the Solar System, 2003 UB_{313} (97 AU from the Sun), was recently discovered near its aphelion[1]. Its high eccentricity and inclination to the ecliptic plane, along with its perihelion near the orbit of Neptune, identify it as a member of the 'scattered disk'. This disk of bodies probably originates in the Kuiper belt objects, which orbit near the ecliptic plane in circular orbits between 30 and 50 AU, and may include Pluto as a member. The optical brightness of 2003 UB_{313}, if adjusted to Pluto's distance, is greater than that of Pluto, which suggested that it might be larger than Pluto[2]. The actual size, however, could not be determined from the optical measurements because the surface reflectivity (albedo) was unknown. Here we report observations of the thermal emission of 2003 UB_{313} at a wavelength of 1.2 mm, which in combination with the measured optical brightness leads to a diameter of 3,000 ± 300 ± 100 km. Here the first error reflects measurement uncertainties, while the second derives from the unknown object orientation. This makes 2003 UB_{313} the largest known trans-neptunian object, even larger than Pluto (2,300 km)[3]. The albedo is 0.60 ± 0.10 ± 0.05, which is strikingly similar to that of Pluto, suggesting that the methane seen in the optical spectrum[2] causes a highly reflective icy surface.

The optical brightness of a planetary object derives from the reflected sunlight, and is therefore directly proportional to the square of the diameter, d, and to the optical surface reflectivity, p, which refers to the visual red and is called the 'red geometric albedo'. These three quantities are related through[4] $d = 1{,}346\ p^{-1/2}\ 10^{-H/5}$ km, where H is the absolute magnitude in the V band (around 540 nm) if the object were seen at a distance of one astronomical unit (1 AU), which is the mean distance between Sun and Earth. The albedo is known to vary significantly between the distant minor planets, ranging from ~0.03 in dark trans-neptunian objects (TNOs)[5,6] to ~0.6 for Pluto[7]. The optical brightness therefore provides only a lower limit to the object size when assuming $p = 1$, which in the case of 2003 UB_{313} (where $H = -1.16$ mag (refs 1, 8), with a current uncertainty of about 0.1 mag) yields $d > 2{,}234$ km. To better constrain the size of a planetary body, it is necessary to measure its thermal emission at a wavelength where the reflected solar flux is negligible. The mm brightness is a function of the surface temperature and object size, and the temperature is only weakly dependent on the surface albedo. To measure the size of 2003 UB_{313}, we observed it at a wavelength of 1.2 mm, where the emission is pure thermal radiation. By combining the observed flux density at mm wavelengths with the optical brightness, one obtains a good determination of the object's diameter and geometric albedo, although some assumptions must be made for the object's unknown rotation period and orientation of the rotation axis.

Our millimetre observations were performed with the Max-Planck

Table 1 | Observation summary

Date in 2005 (day.month)	S_ν(250 GHz) (mJy)	τ_{zenith}	τ_{los}	t_{int} (s)
19.8	1.16 ± 0.49	0.26	0.40	6,937
23.8	0.71 ± 0.66	0.23	0.35	2,937
24.8	1.76 ± 0.54	0.23	0.34	4,273
27.8	1.27 ± 0.49	0.35	0.50	6,166
19–27.8	1.27 ± 0.26			20,313

We observed the object on four dates. Atmospheric conditions were good on 19 August (variable sky-noise), and very good on 23, 24 and 28 August. All data are used in our analysis, except for one 4-min scan during which the chopping failed. Flux densities at 250 GHz are given in mJy = 10^{-26} erg s^{-1} cm^{-2} Hz^{-1}, with a one standard deviation error giving the statistical uncertainties of the integrated measurement, which excludes systematic uncertainties due to flux calibration or pointing errors. The integration time is on-sky, half of which is on-source. The quoted zenith and line-of-sight opacities (τ_{zenith} and τ_{los}, respectively) are averaged over the integration time. The data were analysed with the MOPSIC data reduction package written by R. Zylka at IRAM. Much of the sky noise is eliminated by subtracting a weighted average signal from the neighbouring channels. The sky zenith opacity was determined through skydips, and the flux calibration was performed through frequent measurements of Uranus and Mars, which were near our target and at similar elevation. For the absolute flux calibration on the planets we find a 5% r.m.s. scatter. This calibration uncertainty must be added to the statistical errors (which decrease with integration time) of the target's flux measurement. We increase the calibration uncertainty to 10% to also account for possible pointing errors of up to 2 arcsec.

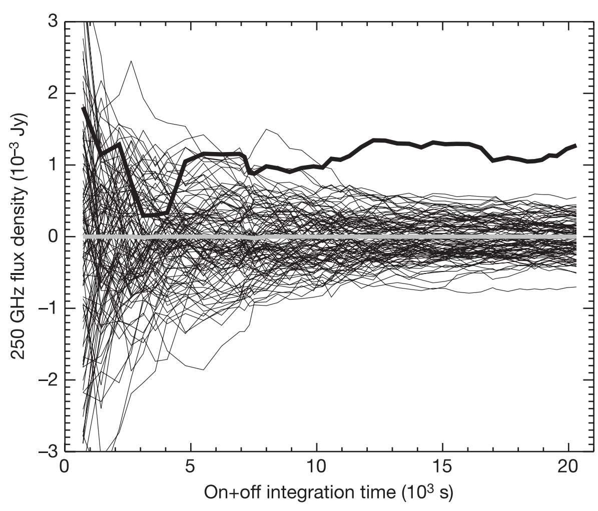

Figure 1 | Time-averaged signals of the 104 bolometers as a function of time, summarizing our 1.2 mm observations. The on-source channel is indicated by a thick black line, the median signal of the off-source channels as a thick grey line. The 117-element MAMBO-2 camera has an effective frequency for thermal radiation of 250 GHz, a half-power bandwidth of 80 GHz (210–290 GHz), and a beam size of 10.7 arcsec (corresponding to 760,000 km at a distance of 96 AU). Observations were performed using the standard on–off technique, with the sub-reflector switching every 0.25 seconds between two sky positions (on and off source) separated by 32 arcsec. The telescope pointing was frequently checked on the 5° distant quasar J0141–095 and was found to be stable within 2 arcsec.

[1]Argelander Institute for Astronomy, University of Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany. [2]Max-Planck-Institute for Radioastronomy, Auf dem Hügel 69, D-53121 Bonn, Germany. [3]IRAM, 300 rue de la Piscine, 38406 Saint Martin d'Hères, France.

Table 2 | Properties of 2003 UB$_{313}$, Pluto, Charon and Ceres

Case	$q = A/p$	d (km)	p	T_b (K)
2003 UB$_{313}$, fast rotation	1	$3,136^{+263}_{-276}$	$0.54^{+0.11}_{-0.08}$	23.2
2003 UB$_{313}$, fast rotation	0.9	$3,094^{+268}_{-286}$	$0.55^{+0.11}_{-0.08}$	23.7
2003 UB$_{313}$, slow rotation	0.9	$2,859^{+231}_{-241}$	$0.65^{+0.11}_{-0.08}$	26.9
Pluto	0.9	2,328 ± 48	0.62 ± 0.02	~36
Charon	0.9	1,242 ± 42	0.37 ± 0.01	40
Ceres	0.4	913 ± 43	0.10 ± 0.01	164

Derived diameter, d, red geometric albedo, p, and brightness temperature, T_b, for different assumptions on rotation and phase integral, q. At mm wavelengths, fast rotation applies for objects seen equator-on and rotating with a period smaller than 40 h, whereas slow rotation applies for those seen pole-on, independent of the rotation period. Data for Pluto[3,7,12], Charon[3,7,12] and Ceres[13] are shown for comparison. Note that for Pluto the red albedo varies between ~0.49 and ~0.75 within each rotation period; for p and T_b we quote mean values.

Millimeter Bolometer (MAMBO-2) array detector at the IRAM 30 m telescope on Pico Veleta, Spain. The object was observed such that its entire emission is collected by one of the camera's horn antennae, and by switching between the object and a blank sky position twice per second. Because of the large, two-beam spacing between the array horns, this photometric (on–off) mode does measure the flux of the object, but does not provide a fully sampled image of the field around it. When averaging our flux density measurements from 19–28 August 2005 (Table 1, Fig. 1), we measure an average flux density of $S_\nu = 1.27 \pm 0.26$ mJy, where the quoted uncertainty is one standard deviation and quantifies only the averaged noise fluctuation in the signal, that is, the significance of the measurement. Systematic uncertainties must be added to this before deriving the object size and albedo. Our spatially unresolved 1.2 mm flux density observation measures the projected surface-integral of the thermal emission of the planetary body. Recent high-resolution optical observations have shown that a moon orbits 2003 UB$_{313}$, an object that is optically ~60 times fainter than the TNO itself[9]. Provided that 2003 UB$_{313}$ and its moon have a similar albedo, the moon contributes less than 2% to the observed mm flux density, a correction that is much smaller than the flux uncertainty.

Assuming that a TNO does not have a significant internal heat source, its surface-integrated thermal emission is in radiation equilibrium with the insolation. We shall further assume that such a small body cannot maintain an atmosphere that could affect the surface temperature. The temperature on the object's side facing the Sun and Earth does depend on its rotation period, the orientation of its rotation axis, and the observation wavelength. In the case of no rotation or when the rotation axis points at the Sun, the temperature on the dayside is higher than in the case of a fast rotator with equatorial view. Most known distant minor planets (TNOs, Centaurs) for which a rotation period was measured have periods of the order of hours[5,10,11]. This justifies the 'fast rotator' approximation (period <2 days) that the effective temperature for mm emission is independent of the 'time of day'[5]. Using Planck's radiation law and the known solar constant, the disk-averaged equilibrium temperature of a body with low heat conductivity and no atmosphere is $T_{eq} = T_0(1 - A)^{1/4}(r)^{-1/2}$, with r in units of AU; for the fast-rotator case, $T_0 = 277$ K is the disk-averaged temperature of a black body at heliocentric distance, $r = 1$ AU; for the slow rotator case, $T_0 = 329$ K. The Bond albedo, $A = q \times p$, where q is the phase integral, is a measure of the total absorbed solar energy. It is different for each Solar System object and must be determined observationally. From millimetre observations[5] the geometric albedo, p, of TNOs is measured to range between 0.03 and 0.16, although some recent Spitzer Space Telescope observations imply even higher values[6]. The phase integral, q, relates the Bond albedo to the geometric albedo, p. Whereas $q \approx 1$ for the brightest and largest TNOs such as Pluto, the smallest TNOs can have $q \approx 0.3$ (refs 10, 11). Even though the uncertainty in q seems large, the effect on the equilibrium temperature, T_{eq}, derived from combined mm and optical measurements is small.

The flux density of the object at geocentric distance Δ is given by $S_\nu = (\pi d^2/4\Delta^2)\ B_\nu(T_b)$, where B_ν is Planck's law and $T_b \approx T_{eq}$ is the brightness temperature. With our observed flux density $S_\nu(250\,\mathrm{GHz}) = 1.27 \pm 0.26$ mJy (to this statistical error we add a 10% calibration uncertainty), the relations between diameter, temperature and albedo cited above can be solved together to yield values for the diameter and albedo. The estimated 0.1 magnitude uncertainty of the optical magnitude, H, adds an additional ~1% error to the diameter and a ~7% error to the albedo. In Table 2 we list the results for different assumptions on the rotation period (or orientation) and phase integral, q. We consider the most likely case to be a fast-rotator with $q = 0.9$, resulting in a geometric albedo value very similar to that of Pluto. If we happen to view the object nearly pole-on, the slow-rotator case would apply, which then implies a smaller radius and higher albedo.

2003 UB$_{313}$ was not detected with the Spitzer Space Telescope at 70 μm wavelength, and an upper limit to the flux density was set by background source confusion (M. E. Brown, C. A. Trujillo and D. Rabinowitz, manuscript in preparation). We can predict the flux density at 70 μm given our size and albedo estimate. Because the thermal timescale of the thin surface layer responsible for the far-infrared emission is probably less than the typical rotation period of TNOs, we consider a range between the fast and slow rotation limit for computing the brightness temperature observed at 70 μm. For our favourite case $q = 0.9$, $d = 3{,}094$ km, $p = 0.55$, we derive a range $S_\nu(70\,\mu\mathrm{m}) = 0.7 - 2.8$ mJy between the fast and slow rotation limits, respectively, which is consistent with the observed Spitzer upper limit. In the slow rotation case, any lower value of q would imply a higher brightness temperature and higher flux density at 70 μm that would not be consistent with the observed limit. In case we actually observe the object pole-on, we predict a radius of 2,859 km and a 70 μm flux density of 1.7 mJy, which is also consistent with the Spitzer upper limit.

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1. Brown, M. E., Trujillo, C. A. & Rabinowitz, D. *IAU Circ.* 8577 (2005).
2. Brown, M. E., Trujillo, C. A. & Rabinowitz, D. L. Discovery of a planetary-sized object in the scattered Kuiper Belt. Preprint at ⟨http://arXiv.org/astro-ph/0508633⟩ (2005)
3. Young, E. F. & Binzel, R. Comparative mapping of Pluto's sub-Charon hemisphere — three least squares models based on mutual event lightcurves. *Icarus* **102,** 134–149 (1994).
4. Bowell, E., *et al.* in *Asteroids II* (eds Binzel, R., Gehrels, T. & Matthews, M.) 549–554 (Univ. Arizona Press, Tucson, 1989).
5. Altenhoff, W., Bertoldi, F. & Menten, K. M. Size estimates of some optically bright KBOs. *Astron. Astrophys.* **415,** 771–775 (2004).
6. Stansberry, J. A. *et al.* Albedos, diameters (and the density) of Kuiper Belt and Centaur objects. *Bull. Am. Astron. Soc.* **37,** 737 (2005).
7. Tholen, D. J. & Tedesco, E. F. Pluto's lightcurve: Results from four oppositions. *Icarus* **108,** 200–208 (1994).
8. JPL HORIZONS on-line solar system data and ephemeris computation service. ⟨http://ssd.jpl.nasa.gov/horizons.html⟩ (accessed November 2005).
9. Brown, M. E. *et al.* Satellites of the brightest Kuiper belt objects. Preprint at ⟨http://arXiv.org/astro-ph/0510029⟩ (2005).
10. Rabinowitz, D. L. *et al.* Photometric observations constraining the size, shape, and albedo of 2003 El61, a rapidly rotating, Pluto-sized object in the Kuiper Belt. Preprint at ⟨http://arXiv.org/astro-ph/0509401⟩ (2005).
11. Sheppard, S. S. & Jewitt, D. C. Time-resolved photometry of Kuiper Belt Objects: rotations, shapes, and phase functions. *Astron. J.* **124,** 1757–1775 (2002).
12. Reinsch, K., Burwitz, V. & Festou, M. C. Albedo maps of Pluto and improved physical parameters of the Pluto-Charon system. *Icarus* **108,** 209–218 (1994).
13. Tedesco, E. F. in *Asteroids II* (eds Binzel, R., Gehrels, T. & Matthews, M.) 1090–1093 (Univ. Arizona Press, Tucson, 1989).

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