The size and albedo of the Kuiper-belt object (20000) Varuna

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Observations over the last decade have revealed the existence of a large number of bodies orbiting the Sun beyond Neptune[1]. Known as the Kuiper-belt objects (KBOs), they are believed to be formed in the outer reaches of the protoplanetary disk around the young Sun, and have been little altered since then. They are probably the source of short-period comets[2]. The KBOs are, however, difficult objects to study because of their distance from earth, so even basic physical properties such as their sizes and albedos remain unknown. Previous size estimates came from assuming an albedo with the canonical value being 0.04. Here we report simultaneous measurements of the thermal emission and reflected optical light of the bright KBO (20000) Varuna, which allow us to determine independently both the size and the albedo. Varuna has an equivalent circular diameter of $D = 900^{+129}_{-145}$ km and a red geometric albedo of $p_R = 0.070^{+0.030}_{-0.017}$. Its surface is darker than Pluto's, suggesting that it is largely devoid of fresh ice, but brighter than previously assumed for KBOs.

The most fundamental physical properties of KBOs are their size and albedo. All published estimates of the sizes of KBOs are on the basis of an assumed albedo of 0.04—the albedo of the cometary nuclei[3–6]—and may be considerably in error[1]. Optical observations provide only a measure of the product of the geometric albedo with the physical cross-section. The albedo and cross-section can be determined separately by combining optical data with a simultaneous measurement of the thermally emitted flux[7]. The thermal emission results from surface heating by sunlight, and varies in proportion to (1 − albedo) times the cross-section. The two constraints supplied by the optical and thermal wavelength observations permit a solution for the two principal unknowns, the albedo and the size. This technique has been applied widely to main-belt asteroids, for which the Planck maximum falls in the observationally accessible 10–20 μm wavelength range. At heliocentric distance $R = 40$ AU, however, the KBOs have equilibrium blackbody temperatures near 45 K and the Planck maximum at 70 μm corresponds to a wavelength at which the atmosphere of the Earth is opaque. Therefore, measurements of thermal emission from KBOs must be taken from space, or through submillimetre windows in the atmospheric transmission. No ground-based thermal observations have been obtained before now owing to the faintness of KBO targets in the atmospheric windows.

The optically bright KBO (20000) Varuna (formerly 2000 WR106) was discovered on 28 November 2000 by the Spacewatch telescope[8]. Observations before discovery dating back to 1954 allowed a quick classification as a classical KBO (ref. 1) with semi-major axis 43.27 AU[9]. Submillimetre observations of (20000) Varuna were obtained using the Submillimeter Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii, on UT 30–31 December 2000 with simultaneous optical photometry from the University of Hawaii 2.2-m telescope. At the time of observation, the heliocentric and geocentric distances of (20000) Varuna were $R = 43.05$ AU and $\Delta = 42.06$ AU, respectively. The phase angle was 0.03°. See Table 1 for the photometric measurements.

The density of faint background galaxy sources brighter than 3 mJy at 850 μm is about 10^3 deg^{-2} (ref. 10). The probability that such a source might fall in the SCUBA beam is about 0.01. As a precaution against this (small) possibility, we took data on two nights so that the motion of (20000) Varuna would prevent any single background object from contaminating the photometry. The probability that two different background objects might contaminate the SCUBA beam on two nights is of the order of 10^{-4} and can therefore be neglected. In addition, we find no galactic source in the Infrared Astronomical Satellite 60-μm survey within 5 arcmin of (20000) Varuna.

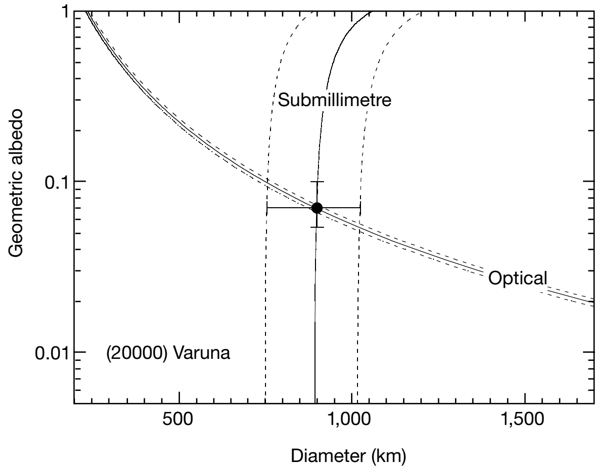

Figure 1 Albedo and diameter constraints from the optical and submillimetre thermal observations of (20000) Varuna.

The weak temperature dependence of the Planck function in the Rayleigh–Jeans limit conveys a significant advantage to the interpretation of submillimetre thermal emission data[11]. Specifically, uncertainties in the spatial distribution of the surface temperature[12] have a minimal effect on the Rayleigh–Jeans emission, whereas their impact on the flux emitted near the Planck maximum can be very strong[13,14]. In the Rayleigh–Jeans limit, the diameter is given by[11]:

$$D = \lambda\Delta\left(\frac{2S_\nu}{\pi k \epsilon_{sm}}\right)^{1/2}\left(\frac{\sigma R^2}{F_{Sun}}\right)^{1/8}\left(\frac{\epsilon_{ir}\chi}{1-A}\right)^{1/8} \quad (1)$$

where $\lambda = 850$ μm is the wavelength of observation, Δ (m) is the geocentric distance, S_ν (W m^{-2} Hz^{-1}) is the measured flux density, $k = 1.38 \times 10^{-23}$ J K^{-1} is Boltzmann's constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is the Stefan–Boltzmann constant, R (AU) is heliocentric distance, and $F_{Sun} = 1{,}360$ W m^{-2} is the solar constant. The emissivity of the surface at submillimetre and thermal infrared (Planck maximum) wavelengths is given by ϵ_{sm} and ϵ_{ir}, respectively. We assume $\epsilon_{sm} = \epsilon_{ir} = 0.9$. The factor χ parametrizes the distribution of temperature over the surface where $\chi = 2$ corresponds to the 'standard thermal model' approximation[15] in which the Sun is on the rotation axis and solar heating is confined to a single hemisphere, whereas $\chi = 4$ corresponds to an isothermal body. The intermediate case, a body illuminated equatorially and having a short rotation period compared with the cooling time (the so-called 'isothermal latitude model') has $\chi = \pi$. We assume $\chi = 2$. Last in equation (1), A is the (dimensionless) bond albedo, related to the geometric albedo by:

$$A = p_R q \quad (2)$$

where q is the 'phase integral' and p_R is the R-band geometric albedo. Measurements of airless planetary bodies suggest $q = 0.75$, with an uncertainty of about 30%[16]. In equation (1) even factor-of-two uncertainties in χ, ϵ_{ir} and $(1 - A)$ correspond to only 10% uncertainties in the derived diameter, owing to the one-eighth power dependence. Equation (1) is more strongly dependent on ϵ_{sm}. Measurements of Ganymede, Callisto and Pluto all suggest $\epsilon_{sm} \approx 0.9$, as used here[11]. A reduced submillimetre emissivity by a

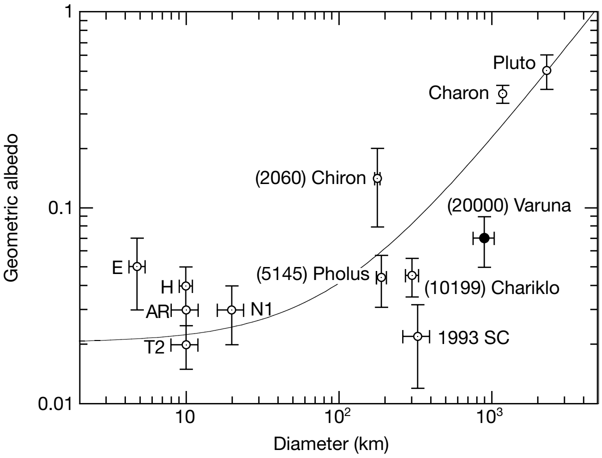

Figure 2 Well determined albedos and diameters of outer Solar System objects. The nuclei of short-period comets are: E, P/Encke[6]; AR, P/Arend-Rigaux[5]; T2, P/Tempel 2 (ref. 4); N1, P/Neujmin 1 (ref. 3); and H, P/Halley[22]. Other objects include centaurs (2060) Chiron[23], (5145) Pholus[24] and (10199) Chariklo[13], and Pluto and Charon[25]. The albedo of Charon should be considered an upper limit, owing to near-nucleus dust coma contamination. A 2.7σ confidence limit to the 90-μm flux from the Infrared Space Observatory on 1993 SC was used to obtain estimates for the diameter (328^{+58}_{-66} km) and albedo ($0.022^{+0.013}_{-0.006}$), while object 1996 TL66 was not detected at its expected position[14]. Thermal observations of KBOs will be an important objective of NASA's upcoming SIRTF satellite. The solid line shows the linear correlation between albedo and diameter. The linear correlation coefficient for the objects is 0.92, and the probability that this or a larger correlation might be obtained by chance from uncorrelated data is $P(0.92,12) < 10^{-4}$. Removal of Pluto from the plot reduces the correlation coefficient to 0.79, for which $P(0.79,11) = 0.004$, which is statistically insignificant (3σ corresponds to $P = 0.003$). Plotted error bars are all 1σ. $P(x,y)$ notation indicates the correlation coefficient, x, and the number of data points, y.

factor of two would increase the derived diameter by $2^{1/2}$ and decrease the albedo by a factor of 2; however, we consider it unlikely that ϵ_{sm} is different from 0.9 by a factor of 2.

The apparent red magnitude, m_R, of a body viewed in scattered sunlight is related to its physical properties by[17]:

$$\phi(\alpha) p_R D^2 = 8.96 \times 10^{22} R^2 \Delta^2 10^{0.4(m_{Sun} - m_R)} \quad (3)$$

where $\phi(\alpha)$ is the phase function at phase angle α (degrees), D (m) is the diameter, R (AU) and Δ (AU) the heliocentric and geocentric distances, respectively, and $m_{Sun} = -27.1$ is the red magnitude of the Sun. The phase angle is small so that we may set $\phi(0.03°) = 1$. The optical photometry provides, through equation (3), a constraint on the product $p_R D^2$.

The trajectories defined by equations (1) and (2) are plotted in Fig. 1. The trajectories intersect at $D = 900^{+125}_{-145}$ km, $p_R = 0.070^{+0.030}_{-0.017}$, which we take as the best estimate of the diameter and albedo of (20000) Varuna. The quoted uncertainties reflect only statistical errors. The optical brightness of (20000) Varuna varies by 0.5 mag (50%) with a period near 3 h (ref. 18), and the phase of the optical light curve at the time of our observations is unknown. This introduces a systematic uncertainty into the derived albedo of up to 50%. A further uncertainty of the order of 10% is introduced by the small phase angle at the epoch of observation (Table 1) and by the unknown magnitude of the opposition surge[19].

Figure 2 compares the albedos and diameters of a number of well studied bodies in the outer Solar System. The observations show a trend towards higher albedos at larger sizes. The small cometary nuclei are the darkest of the observed bodies, whereas Pluto and its satellite Charon are the most reflective. This trend is highly statistically significant but disappears when Pluto is removed from the sample (Fig. 2, legend). The globally high albedo of Pluto is the result of surface frosts freshly deposited from a tenuous atmosphere. The smaller (20000) Varuna, with a radius 40% that of Pluto and perhaps only 6% of Pluto's mass, has insufficient gravity to retain an atmosphere, and consequently lacks a global surface frost. Patchy frost distributions are not excluded, however, and would be compatible with the recently measured large, rotational lightcurve[18]. □

Table 1 Photometry of (20000) Varuna

Date (UT)	Telescope	Wavelength	Flux density/magnitude
2000 December 30.4764–30.5625	JCMT	850 μm	3.14 ± 1.10 mJy
2000 December 31.4896–31.5764	JCMT	850 μm	2.37 ± 1.29 mJy
Combined		850 μm	2.81 ± 0.85 mJy
2000 December 30.4757	UH 2.2 m	0.65 μm	19.7 ± 0.1 mag

The JCMT provides diffraction-limited (14 arcsec full width at half maximum (FWHM)) resolution images at $\lambda = 850$ μm. We used the SCUBA camera[20] in photometry mode with hourly pointing and photometric calibration obtained from nearby fixed objects CRL618, 0.745+241 and OJ287. The pointing was accurate to ±2 arcsec, while the ephemeris accuracy was better than 1 arcsec. The telescope was tracked on the motion of (20000) Varuna, at about 3.1 arcsec h^{-1} westward, using software to interpolate the motion. Atmospheric opacity was monitored using skydips made with the JCMT and with a radiometer at the nearby Caltech Submillimetre Observatory. The 230 GHz optical depth of the atmosphere varied in the range 0.065–0.080, corresponding to a water column abundance of about 1.5 mm. Sky cancellation was achieved by chopping to a position 90 arcsec from the source in elevation at a frequency of 7.8 Hz. Accumulated observations of about 5 h were secured on (20000) Varuna. Optical observations were taken at the UH 2.2-m telescope, in the period UT 30.4715–30.5368 December 2000. The 'Orbit' 2048 × 2048 pixel charge-coupled device was used, with image scale 0.28 arcsec per binned pixel. The flat-fielded red (0.65 μm) filter images were photometrically calibrated using observations of stars from ref. 21. Integration time was 180 s.

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