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Albedo and atmospheric constraints of dwarf planet Makemake from a stellar occultation

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Pluto and Eris are icy dwarf planets with nearly identical sizes, comparable densities and similar surface compositions as revealed by spectroscopic studies[1,2]. Pluto possesses an atmosphere whereas Eris does not; the difference probably arises from their differing distances from the Sun, and explains their different albedos[3]. Makemake is another icy dwarf planet with a spectrum similar to Eris and Pluto[4], and is currently at a distance to the Sun intermediate between the two. Although Makemake's size (1,420 ± 60 km) and albedo are roughly known[5,6], there has been no constraint on its density and there were expectations that it could have a Pluto-like atmosphere[4,7,8]. Here we report the results from a stellar occultation by Makemake on 2011 April 23. Our preferred solution that fits the occultation chords corresponds to a body with projected axes of 1,430 ± 9 km (1σ) and 1,502 ± 45 km, implying a V-band geometric albedo $p_V = 0.77 \pm 0.03$. This albedo is larger than that of Pluto, but smaller than that of Eris. The disappearances and reappearances of the star were abrupt, showing that Makemake has no global Pluto-like atmosphere at an upper limit of 4–12 nanobar (1σ) for the surface pressure, although a localized atmosphere is possible. A density of 1.7 ± 0.3 g cm^{-3} is inferred from the data.

Stellar occultations allow detection of very tenuous atmospheres and can provide accurate sizes and albedos[9,10,11,3,12], so we embarked on a programme of predicting and observing occultations by (136472) Makemake, also known as 2005 FY_9. The occultation of the faint star NOMAD 1181-0235723 (with magnitude $m_R = 18.22$, where NOMAD is the Naval Observatory Merged Astronomic Dataset) was predicted in 2010 by methods similar to those used to predict occultations by several large bodies[13], but refined as shown in Supplementary Information section 1. We arranged a campaign involving 16 telescopes, listed in Supplementary Table 1. The occultation was successfully recorded from seven telescopes, listed in Table 1, at five sites. From the images obtained, we made photometric measurements as a function of time (light curves).

The light curves of the occultation are shown in Fig. 1. Fitting synthetic square-well models to the light curves yielded the disappearance and reappearance times of the star (Table 1), from which we calculate one chord in the plane of the sky for each site (see Supplementary Information section 3). On the basis of analyses of the light curves, taking into account the cycle time between the images and the dispersion of the data, we deduce that there were no secondary occultations, so we can reject the existence of a satellite larger than about 200 km in diameter in the areas sampled by the chords. The result is consistent with a deep-image survey that did not find any satellites[16]. The chords can be fitted with two shape models (Fig. 2). Our preferred shape, which is compatible with our own and other observations (see Supplementary Information section 8), corresponds to an elliptical object with projected axes of 1,430 ± 9 km and 1,502 ± 45 km. By combining this result with visible photometry at various phase angles[17], we calculated that Makemake has a V-band geometric albedo of $p_V = 0.77 \pm 0.03$ (see Supplementary Information section 4). This is considerably high compared to albedos of other trans-Neptunian objects (TNOs)[5], and is larger than that of Pluto ($p_V = 0.52$)[18] but smaller than that of Eris ($p_V = 0.96$)[3].

The object is large enough to be in hydrostatic equilibrium, so it is possible to use the figures of equilibrium formalism, as done for Haumea[19], to analyse the shape of a body that rotates with Makemake's period of 7.77 h (refs 20, 21). The object could only be a triaxial Jacobi ellipsoid for densities in the range 0.66–0.86 g cm^{-3} (for example, ref. 22). Such low densities are unrealistic for a body as large as Makemake (see Supplementary Fig. 7). Thus, Makemake must be an oblate Maclaurin spheroid for plausible densities between 1.4 and 2.0 g cm^{-3} (see discussion in Supplementary Information section 8).

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Table 1 | Details of the successful observations on 2011 April 23

Site and telescope	Pixel scale (″)	Integration time (s)	Filter name	Dead time (s)	Instrument name/detector	Immersion time (UT)	Emersion time (UT)	Longitude/Latitude/Height
La Silla, 3.5 m NTT	0.35	0.272	r′	0.0036	ULTRACAM channel r′	1:35:44.59 ± 0.07	1:36:43.51 ± 0.08	289° 15′ 58.5″ E/ 29° 15′ 31.8″ S/2,345.4 m
La Silla, 3.5 m NTT	0.35	0.272	g′	0.0036	ULTRACAM channel g′	1:35:44.64 ± 0.04	1:36:43.66 ± 0.07	289° 15′ 58.5″ E/ 29° 15′ 31.8″ S/2,345.4 m
La Silla, 0.6 m TRAPPIST	0.64	5	Clear	1.435	FLI- PL3041BB	1:35:46.82 ± 1.6	1:36:45.47 ± 1.6	289° 15′ 38.2″ E/ 29° 15′ 16.6″ S/2,317.7 m
Paranal, 8 m VLT	0.148	1.521	J	0	ISAAC	1:35:46.00 ± 0.35	1:36:49.60 ± 0.35	289° 35′ 50.1″ E/ 24° 37′ 30.3″ S/2,635 m
Armazones, 0.84 m	0.57	10	Clear	3.5	SBIG-STL6303E	1:35:46.30 ± 1.1	1:36:48.52 ± 3	289° 48′ 13.6″ E/ 24° 35′ 51.9″ S/2,705.7 m
San Pedro de Atacama, 0.5 m Harlingten	1.61	5	Clear	1.048	Apogee U42	1:35:37.86 ± 2.7	1:36:43.56 ± 3.1	291° 49′ 13.0″ E/ 22° 57′ 12.2″ S/2,305 m
San Pedro de Atacama, 0.4 m ASH2	1.21	15	Clear	5.966	SBIG-STL11000	1:35:38.66 ± 4	1:36:41.16 ± 2	291° 49′ 13.0″ E/ 22° 57′ 12.2″ S/2,305 m
Pico Dos Dias, 0.6 m Zeiss	1.98	5	Clear	3.851	SITe SI003AB	1:33:57.27 ± 1.6	1:35:01.08 ± 2.2	314° 25′ 02.5″ E/ 22° 32′ 07.8″ S/1,810 m

Image sequences were obtained with all the telescopes at different image rates and with different dead times, as shown. All the observations were made in the visible, except for the Paranal light curve, which was obtained with ISAAC, a near-infrared instrument[14]. The sequences were started typically 20 min before the nominal occultation time, and finished around 20 min later. The images were bias subtracted and flat-field corrected using calibration frames taken before or after the occultation. From the image sequences, fluxes of the combined light source formed by Makemake and the blended star were obtained. The fluxes were obtained by means of synthetic circular-aperture photometry techniques, and the fluxes of other stars in the field of view were extracted using the DAOPHOT package[15]. The fluxes as a function of time constitute what we call light curves. These were divided by the fluxes of other stars to compensate for transparency fluctuations in the terrestrial atmosphere. The resulting light curves were divided by the average value of the unocculted part of the light curve to obtain a normalized flux. The uncertainties in the fluxes were obtained from the standard deviation of the data outside the occultation drop. The computers that controlled the cameras were all periodically synchronized with UT time servers, except for ULTRACAM at the 3.5-m NTT, the timing of which was directly synchronized by means of a global positioning system that provided a time accuracy better than 1 ms. We tested the accuracy of the timing of the Internet-synchronized computers by checking the error logs. The maximum deviations of the computer clocks were all less than 10 ms. Thus we adopt this value as a conservative estimate of the error in the times of the images.

Thermal measurements indicate that Makemake must have two terrains with very different albedos[5,6,23], and a diameter of 1,420 ± 60 km (ref. 6) if assumed to be spherical. This value is in agreement with, but considerably less precise than, the value of 1,430 ± 9 km determined here under the assumption of spherical shape. One of the terrains in the thermal models must be very dark to explain Makemake's thermal

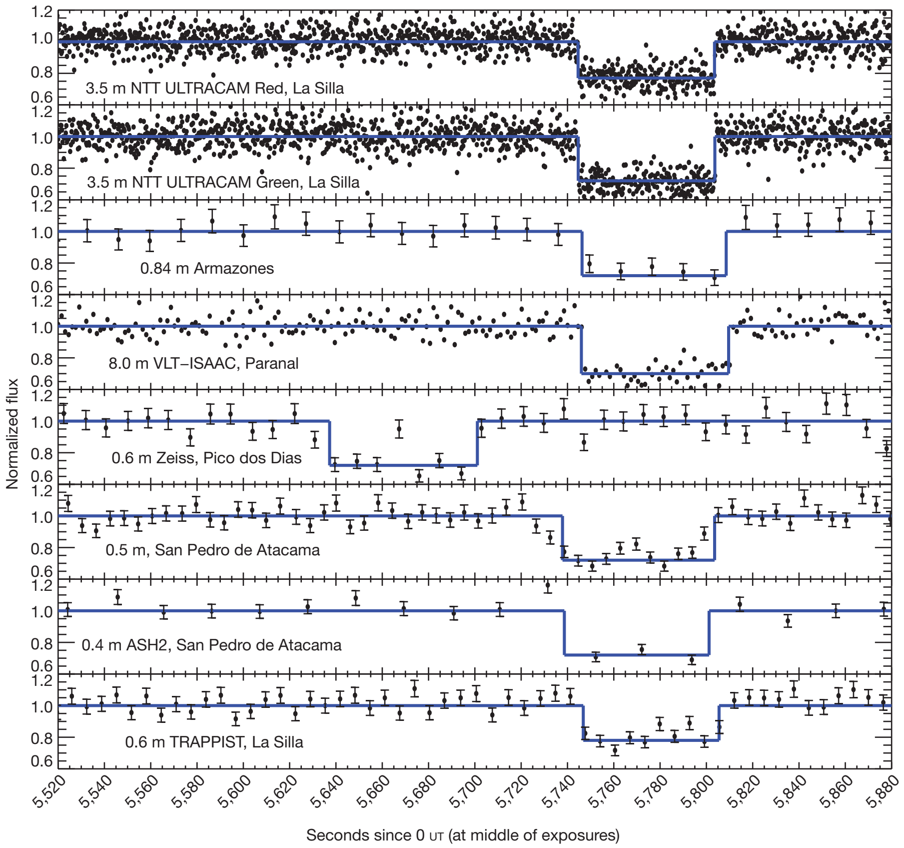

Figure 1 | Light curves of the Makemake event observed from seven telescopes on 2011 April 23. Note that the brightness drop in the Pico dos Dias light curve happens earlier than the rest because the observatory is at a very different longitude (see map in Supplementary Fig. 1). Also note that the ULTRACAM camera provided two channels of useful data (one in the red and the other in the green part of the spectrum). The light curves show the sum of the star and Makemake fluxes, arbitrarily normalized to unity outside the occultation. The R-band star magnitude is about 18.22 according to the NOMAD catalogue, compared with roughly 17.2 for Makemake. Therefore, the expected brightness drop was around 0.35 in normalized flux, as observed. The error bars are 1σ. The NTT and Very Large Telescope Infrared Spectrometer and Array Camera (VLT-ISAAC) light curves are shown without error bars. The blue lines show square-well models that fit the observations, from which the occultation chords of Fig. 2 are obtained. Possible features in the centre of the occultation light curves are analysed in the Supplementary Information. TRAPPIST, Transiting Planets and Planetesimals Small Telescope.

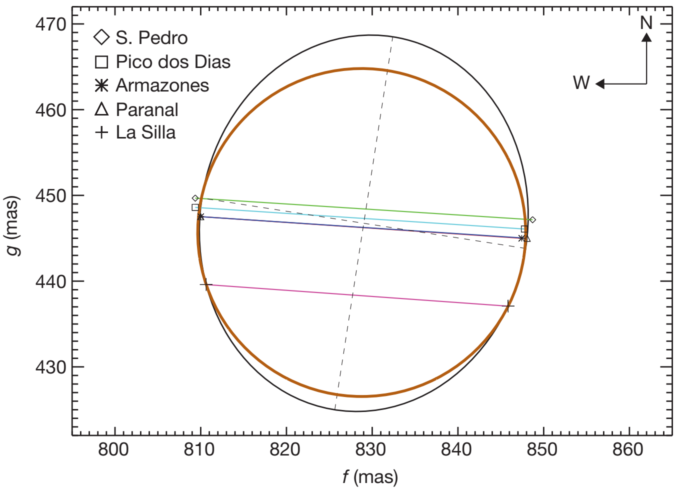

Figure 2 | Occultation chords obtained at five different sites plotted in the projected plane of the sky. The axis marked *g* indicates the north–south direction in the projected plane of the sky; *f* indicates the east–west direction. Units are milliarcseconds (mas). Note that the Paranal and Armazones chords almost overlap. The Paranal, Armazones, Pico dos Dias and San Pedro chords sampled the central part of Makemake. The star disappearance takes place on the left. The chord extremities can be fitted by two different models. The first (pictured in brown) is a circle of diameter 38.28 ± 0.22 mas (1σ level), equivalent to 1,430 ± 9 km, with a reduced χ^2 of 1.032. The second (pictured in black) is an ellipse with a minor axis of 1,428 ± 17 km and an axial ratio of 1.15 ± 0.17, with the long axis tilted by 9 ± 24° (1σ level) with respect to the local celestial north. The reduced χ^2 of the fit is 1.027. The dashed line shows the axes of the best-fitting ellipse. As discussed in the Supplementary Information, the best shape is between the two models. Makemake was 51.5 AU from Earth and 52.21 AU from the Sun at the time of the occultation.

output at 24 µm (ref. 6), which requires a warm terrain on the order of 50 K (see Supplementary Information section 5). The two terrains and Makemake's low rotational variability[20,21,24] can be reconciled if the object is rotating nearly pole-on, if the dark terrain is spread uniformly in longitude (a banded configuration) or by a combination of both conditions.

Makemake is, a priori, a good candidate to have a fully developed atmosphere[4,7,8]. Its albedo and distance from the Sun lie between those of Pluto (which has a global atmosphere) and Eris (which does not, at least currently). Makemake may also have a similar surface composition to Pluto and Eris, on the basis of spectroscopic observations[4]. At the warm temperatures of about 50 K expected from two-terrain thermal models, methane vapour pressure is on the order of a few microbars, whereas nitrogen vapour pressure is around two orders of magnitude higher (as illustrated in Fig. 32 of a work on vapour pressures[25]).

However, a global Pluto-like atmosphere is ruled out by our occultation light curves, which have abrupt ingress and egress profiles (Fig. 1). To get an upper limit on a global atmosphere, it is possible to model its effects on occultation profiles and compare them with observations. The profiles from the New Technology Telescope (NTT) imply an upper limit to the surface pressure of a putative methane atmosphere of only 4–12 nbar at a 1σ confidence level, and 20–100 nbar at the 3σ level (see Fig. 3 and Supplementary Information section 6 for a description of the models, which also consider nitrogen).

One possibility that might explain the lack of a global atmosphere is that Makemake has little or no N_2 ice, because N_2 vapour pressure is well above the microbar level even on the cooler terrain. From an update of the results of the models on retention of volatiles[8], considering new empirical determinations of the vapour pressures of N_2 and CH_4 (ref. 25), Makemake would not have retained N_2 if it were smaller than 1,370 km, which we rule out. With a diameter of 1,430 km, Makemake would have to have a density of less than 1.7 g cm^{-3}, smaller than the adopted nominal value of 1.8 g cm^{-3} (ref. 8), to result in complete N_2 loss. Considering now that CH_4 is abundant on the surface of Makemake, again from the volatile-retention arguments, its density would have to be greater than 1.4 g cm^{-3}. Other constraints on the density based on the observed shape and the figures of equilibrium are discussed in Supplementary Information section 8. Another

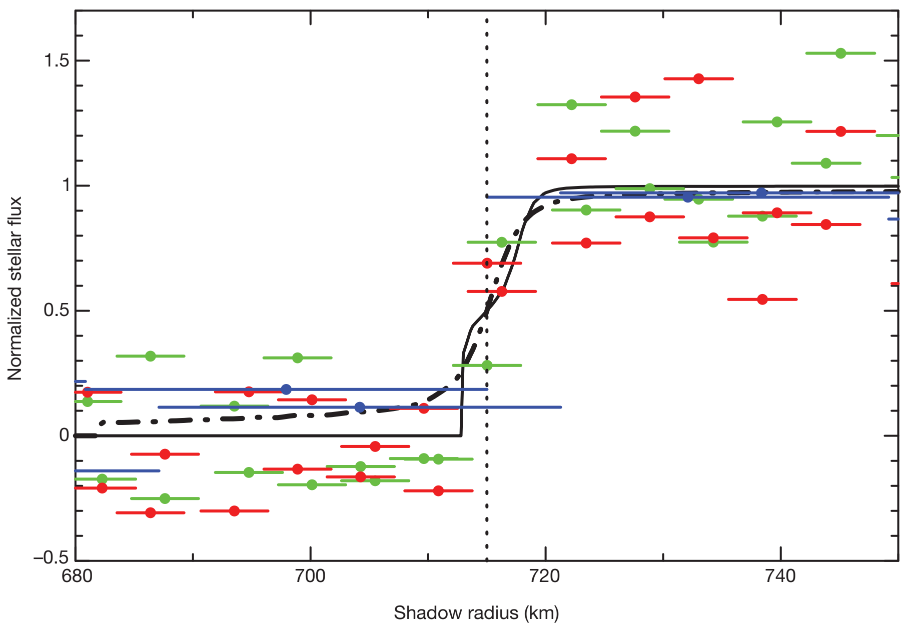

Figure 3 | Observed and synthetic light curves. A comparison of two CH_4 pure atmosphere models with data (ingress and egress profiles: green, NTT g′ points; red, NTT r′ points; blue, VLT J-band) plotted against the distance to Makemake's shadow centre, assuming a circular limb for simplicity. Bars are the radius intervals corresponding to each integration bin. For better reading, and in contrast to Fig. 1, the fluxes have been normalized between zero (average value of the flux during the occultation) and unity (full stellar flux). The models correspond to a CH_4 atmosphere with a surface temperature of 30 K, a near-surface temperature gradient of 17 K km^{-1} followed by an isothermal profile with T = 100 K for higher altitudes. Solid line: surface pressure of P_{surf} = 8 nanobar, compatible with the data at 1σ. Dash-dotted line: model with P_{surf} = 100 nanobar (compatible with the data at 3σ). See Supplementary Information for a full description of the models.

possibility to explain the lack of a global atmosphere is a nearly pole-on orientation. From a theoretical study[7], TNOs with high obliquity are less likely to have globally distributed atmospheres.

The remarkably high albedo of Eris ($p_V = 0.96$) is thought to be the result of a collapsed atmosphere, which coated Eris with bright, fresh ices[3,26]. A fully condensed atmosphere on Makemake might have resulted in an albedo similar to that of Eris, which is not the case. However, if Makemake had a local rather than a global atmosphere, some parts of the surface could be fully covered with fresh ice from the collapsed part of the atmosphere and be very bright, and others could remain dark. The overall albedo of Makemake could thus be smaller than that of Eris, but larger than that of Pluto. A local atmosphere would also provide a reason for the two-terrain models needed to explain Makemake's thermal data.

Local atmospheres on TNOs are theoretically plausible[7]; they can be confined to a subsolar region or a band at the subsolar latitude. It should be noted that a small drop of only 10 K in surface temperature implies a decrease of three orders of magnitude in the vapour pressure of CH_4 and N_2 at low temperatures.

We can investigate whether the presence of a local atmosphere is consistent with our data. The bottom of the occultation light curves should be flat in an airless body. Flashes in occultations are known to be caused by the focusing effect of an atmosphere when the observer passes near the centre of the shadow[27]. Thus, the noise level of the light curves at their bottoms can put limits on the local atmosphere that can extend to the limbs. Modelling of central flashes for plausible local atmospheres shows that an atmosphere with surface pressure on the order of several microbars can exist and still be consistent with the data, provided that the atmosphere is confined to specific parts of the limb (see Supplementary Information section 7).

From the information gathered on Pluto, Eris and now Makemake using stellar occultations, we hypothesize that the albedos and other surface properties of the largest TNOs are determined by sublimation and condensation processes. In our picture, the largest albedos would result from atmospheres that have fully condensed (collapsed onto the surface), whereas medium-albedo objects would have local atmospheres and the lower-albedo objects would have global atmospheres from sublimation of the volatiles. Future studies will shed light on this possibility and whether sublimation is fully solar driven or is also driven by other mechanisms. The airborne Stratospheric Observatory For Infrared Astronomy, in combination with large aperture telescopes on the ground, would be an excellent tool for this kind of study.

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Supplementary Information is available in the online version of the paper.

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