No global Pluto-like atmosphere on dwarf planet Makemake from a stellar occultation

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Pluto and Eris are icy dwarf planets with nearly identical accurately measured sizes, comparable densities, and similar surface compositions as revealed by spectroscopic studies[1,2]. Their different albedos[3] and current distances from the Sun are likely reasons why Pluto possesses an atmosphere whereas Eris does not. Makemake is another icy dwarf planet with a similar spectrum to Eris and Pluto[4] and is currently at intermediate distance to the Sun between the two. Makemake's size and albedo were known approximately[5,6], there was no constraint on its density and there were expectations that it could have a Pluto-like atmosphere[4,7,8]. Here we present results from a stellar occultation by Makemake on 2011 April 23rd. 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±0.03. This albedo is larger than that of Pluto, but smaller than that of Eris. The star disappearances and reappearances were abrupt, showing that Makemake has no global Pluto-like atmosphere at an upper limit of 4 to 12 nbar (1σ) for the surface pressure. The possibility of a localized atmosphere is investigated, and viable scenarios are proposed. A density of 1.7±0.3 g cm^{-3} is implied by the data.

Because stellar occultations allow detecting very tenuous atmospheres and can provide accurate sizes as well as albedos[9,10,11,3,12], we embarked on a program to predict and observe 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) was predicted in 2010 by following similar methods to those recently 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 S1. The occultation was successfully recorded from 7 telescopes, listed in table 1, at 5 sites. From the images obtained, photometric measurements as a function of time (light curves) were obtained for each instrument.

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 shown in table 1. These times provided chords in the plane of the sky, one chord per site (see Supplementary Information, section 3). Because there were no secondary occultations we can reject the existence of a satellite larger than ~200 km in diameter in the areas sampled by the chords. This comes from the analyses of the light curves, taking account the cycle time between the images and the dispersion of the data. The result is consistent with a deep image survey that did not find any satellites[16]. The chords can be fit with two shape models (Fig. 2). Our preferred shape that is compatible with our own and other observations (see Supplementary Information, section 8) corresponds to an elliptical object with projected axes 1,430±9 km and 1,502±45 km. By combining this result with visible photometry at various phase angles[17], it turns out that Makemake has a V-band geometric albedo of p_V=0.77±0.03 (see Supplementary Information, section 4). This considerably high albedo compared to that of the Trans-Neptunian Objects (TNOs) population[5] is larger than that of Pluto (p_V=0.52)[18] but smaller than that of Eris (p_V=0.96)[3].

Because the object is large enough to be in hydrostatic equilibrium one can use the figures of equilibrium formalism as done for Haumea[19] to analyze the shape of a body that rotates at Makemake's period of 7.77 hours[20,21]. The object could only be a tri-axial Jacobi ellipsoid for densities in the range 0.66 to 0.86 g cm^{-3} (e.g. ref. 22). Such low densities are unrealistic for a body as large as Makemake (see Fig. S7 of Supplementary Information). 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).

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 1,430±9 km value 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 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 the low rotational variability of Makemake[20,21,24] can be reconciled if the object is rotating nearly pole-on or if the dark terrain is spread uniformly in longitude (a banded configuration) or a combination of both.

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 presently). Makemake may also have a similar surface composition to Pluto and Eris based on spectroscopic observations[4]. At the warm ~50 K temperatures expected from the two-terrain thermal models, methane vapour pressure is a few μbar while nitrogen vapour pressure is around 2 orders of magnitude higher (as illustrated in Fig. 32 of a recent work on vapor pressures[25]).

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

To explain the lack of a global atmosphere a possibility is that Makemake might have little or no N_2 ice, because N_2 vapour pressure is well above the μbar level even at the cooler terrain. From an update of the results of the models on retention of volatiles[8] considering new empirical determinations of the vapor 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. A density of 1.7 g cm^{-3}, smaller than the adopted nominal 1.8 g cm^{-3} value[8], would result in complete N_2 loss for a body with a 1,430 km diameter. Under this view Makemake would have a density smaller than 1.7 g cm^{-3}. Considering now that CH_4 is abundant on the surface of Makemake, again from the volatile retention arguments, its density would 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 section 8 of the Supplementary Information. Another 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 a result of a collapsed atmosphere which coated Eris with bright fresh ices[3,26]. A fully condensed atmosphere on Makemake might have resulted in a similar albedo to that of Eris, which is not the case. If Makemake had a local, not 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 whereas others could not. The overall albedo of Makemake could thus be smaller than that of Eris, but larger than that of Pluto. A local atmosphere can 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 locally confined to a subsolar region or a band at the subsolar latitude. One should note 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 of the order of several μbar 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 fully condensed atmospheres (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 SOFIA observatory in combination with large aperture telescopes on the ground can be an excellent tool for this kind of studies.

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SUPPLEMENTARY INFORMATION is linked to the online version of the paper at www.nature.com/nature

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AUTHOR CONTRIBUTIONS

J.L.O. helped plan the campaign, analysed data for the prediction, made the prediction, participated in the observations, obtained and analysed data, interpreted the data and wrote part of the paper. B.S. helped plan the campaign, participated in the observations, analysed data, interpreted data, wrote and ran the diffraction and ray-tracing codes, and wrote part of the paper. F.B.-R., and A.A.-C. helped plan the campaign, participated in the observations, analysed and interpreted data. E.L. analysed the implications of the results for Makemake's thermal model and putative atmospheric structure, and wrote part of the paper. R.D. and V.D.I. helped planning the observations and analysed data. J.I.B.C., S.P.L., E.U.-S. J.P.C. E.J., J.M. participated in the observations and analysed data. M.A., F.B.-R., J.I.B.C., R.V.M., D.N.d.S.N. and R.B. discovered the star candidate and analysed data. P. G. and T. M. made thermal models and participated in the interpretation. All other authors participated in the planning of the campaign and/or the observations and/or the interpretations. All authors were given the opportunity to review the results and comment on the manuscript.

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Table 1. Details of the successful observations on 2011 April 23. Image sequences were obtained with all the telescopes at different image rates and with different dead times as shown in the table. All the observations were carried out 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 minutes prior to the nominal occultation time, and finished around 20 minutes 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. Also, the fluxes of other stars in the field of view were extracted. We used the DAOPHOT package[15] to extract them. 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 un-occulted 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 UTC time servers, except for ULTRACAM at the 3.5m NTT telescope, whose timing was directly synchronized by means of a GPS 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 below 10 ms. Thus we adopt this value as a conservative estimate of the error in the times of the images.

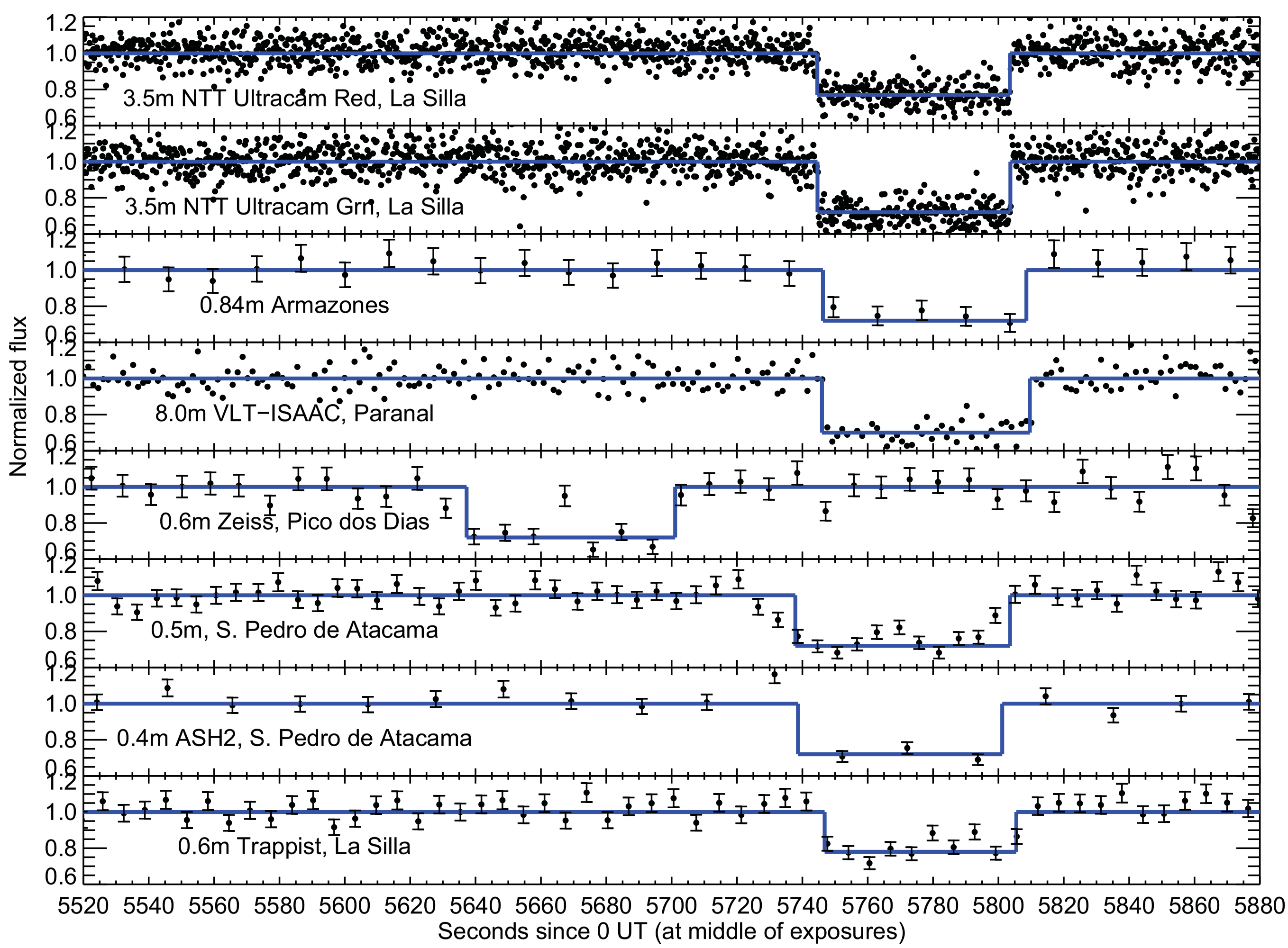
Site and Telescope	Pixel scale (“)	Integration time (s)	Filter name	Dead time (s)	Instrument name/ detector	Immersion time UTC	Emersion time UTC	Longitude Latitude Height
La Silla, 3.5m NTT	0.35	0.272	r’	0.0036	ULTRACAM channel r’	1:35:44.59±0.07	1:36:43.51±0.08	289°15'58.5"E, 29°15'31.8"S, 2345.4 m
La Silla, 3.5m 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, 2345.4 m
La Silla, 0.6m 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, 2317.7 m
Paranal, 8m 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, 2635 m
Armazones, 0.84m	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, 2705.7 m
S. 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, 2305 m
S. Pedro de Atacama 0.4m 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, 2305 m
Pico Dos Dias, 0.6m 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, 1810 m

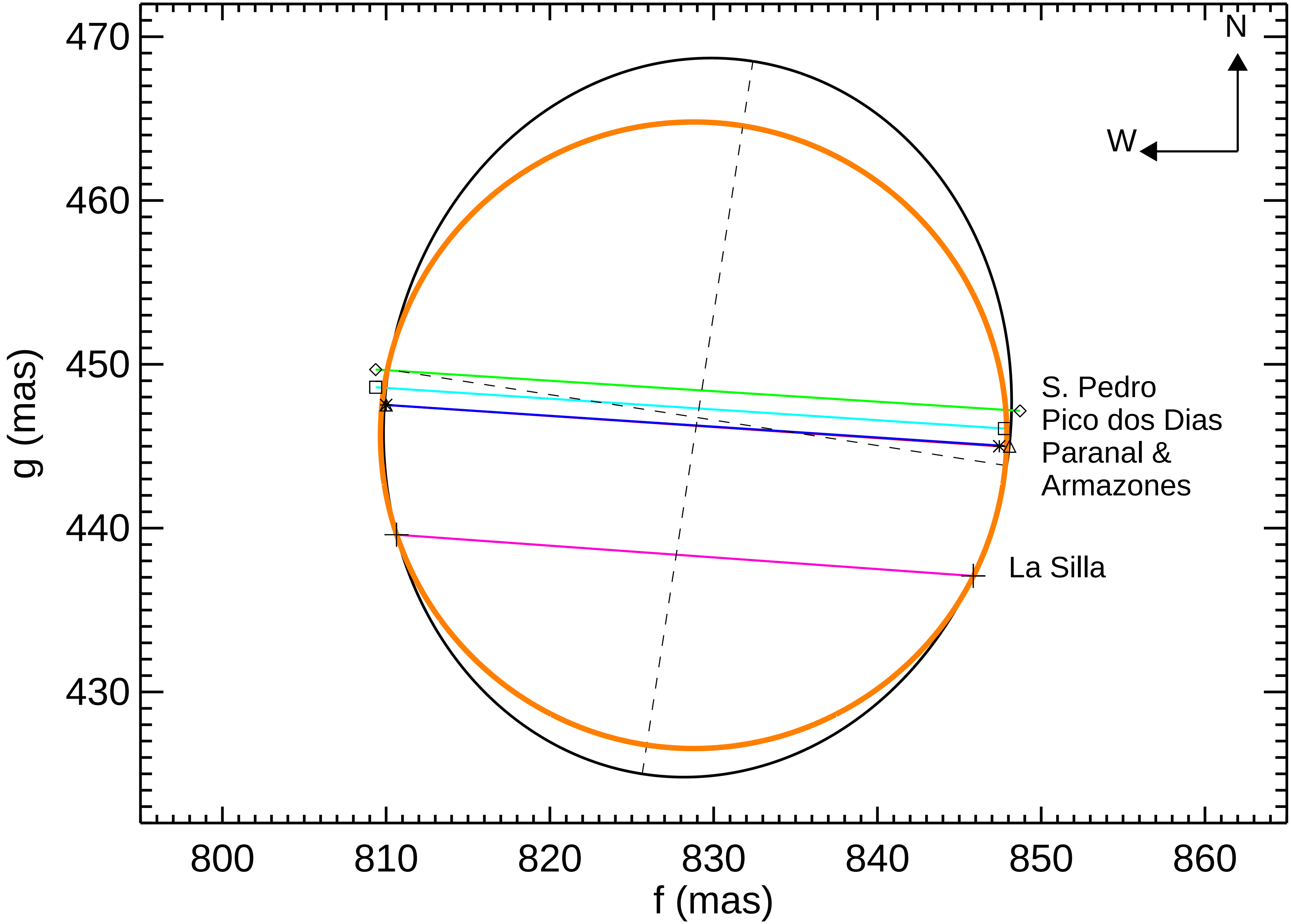
Fig. 1. Light curves of the Makemake event observed from 7 telescopes on April 23rd 2011. Note that the brightness drop in the Pico dos Dias light curve happens earlier than the rest because the observatory is at a very different longitude on Earth than the rest (see map in Fig. S1 of the supplementary information). 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 ~18.22 according to the NOMAD catalogue vs. ~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 VLT light curves are shown without error bars. The blue lines show square well models that fit the observations and 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.

Fig. 2. Occultation chords obtained at 5 different sites plotted in the projected plane of the sky. The *g* axis indicates the North-South direction in the projected plane of the sky and the *f* axis 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 S. Pedro chords sampled the central part of Makemake. The star disappearance takes place in the left part of the plot. The chord extremities can be fitted by two different models: 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.

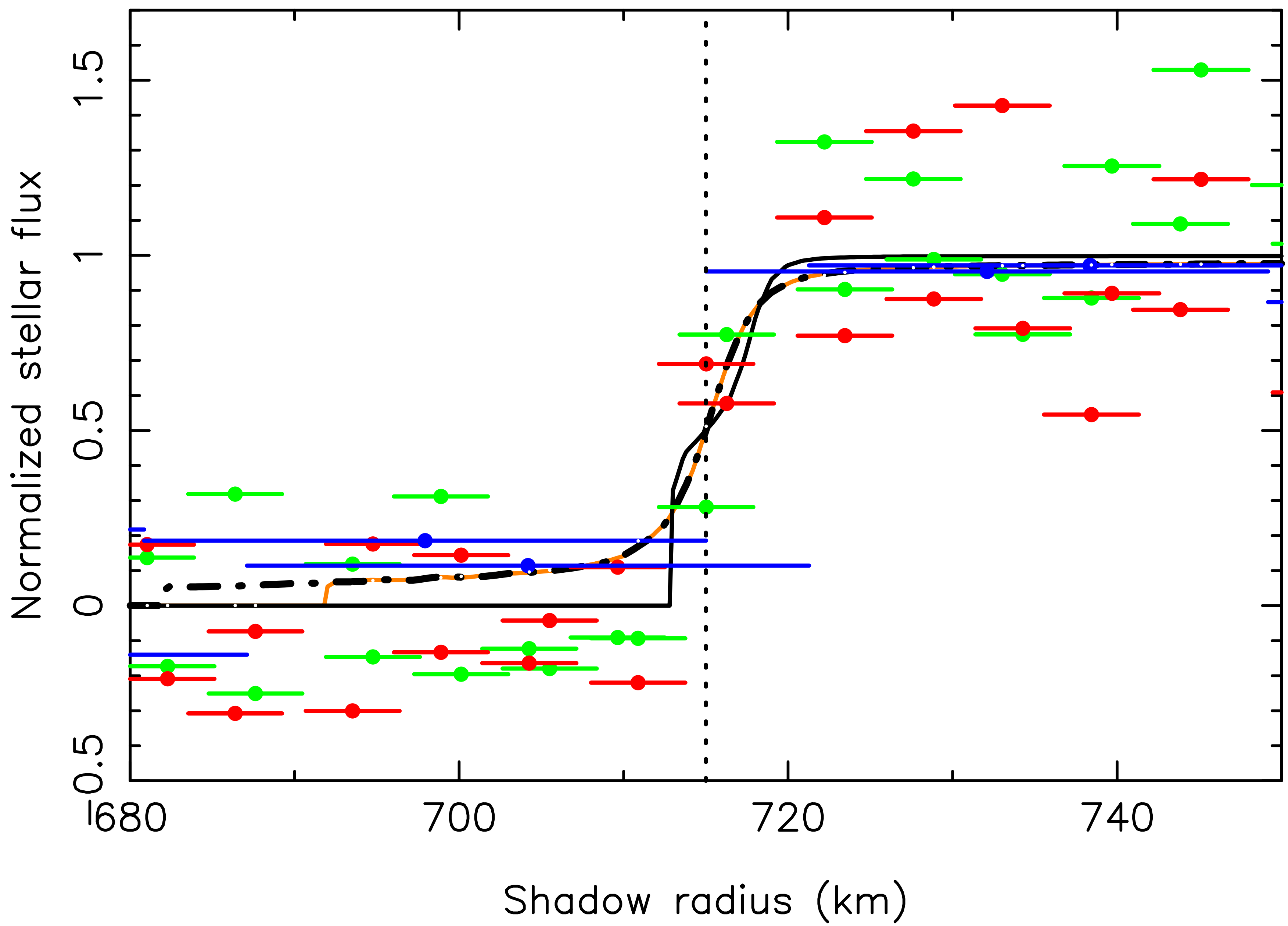
The brown line is the fit to a circle. An ellipse model can also fit the limb of Makemake. The ellipse that fits the chords best is the black line. The fit corresponds to a minor axis of 1,428±17 km and an axial ratio of 1.15±0.17 with the long axis of the ellipse tilted by 9±24 degrees (1σ level) with 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. The distances of Makemake from the Earth and the Sun at the time of the occultation were 51.5 AU and 52.21 AU respectively.

Fig. 3. Observed and synthetic lightcurves. A comparison of two CH_4 pure atmosphere models with data (ingress and egress profiles) is made here. The data (colored points) are plotted versus the distance to Makemake's shadow centre assuming a circular limb for simplicity, while the bars are the radius intervals corresponding to each integration bin (green: NTT g' points, red: NTT r' points, blue: VLT J-band). For better reading, and contrarily 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 nbar, compatible with the data at 1σ. Dashed-dotted line: model with P_{surf} = 100 nbar (compatible with the data at 3σ). See supplementary information for a full description of the models.


3.5m NTT Ultracam Red, La Silla
3.5m NTT Ultracam Grn, La Silla
0.84m Armazones
8.0m VLT−ISAAC, Paranal
0.6m Zeiss, Pico dos Dias
0.5m, S. Pedro de Atacama
0.4m ASH2, S. Pedro de Atacama
0.6m Trappist, La Silla
Normalized flux
Seconds since 0 UT (at middle of exposures)



470
460
450
440
430
g (mas)
800
810
820
830
840
850
860
f (mas)
N
W
S. Pedro
Pico dos Dias
Paranal &
Armazones
La Silla


Normalized stellar flux
1.5
1
0.5
0
0.5
680
700
720
740
Shadow radius (km)