The size, shape, density and ring of the dwarf planet Haumea from a stellar occultation

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Haumea—one of the four known trans-Neptunian dwarf planets—is a very elongated and rapidly rotating body1–3. In contrast to other dwarf planets4–6, its size, shape, albedo and density are not well constrained. The Centaur Chariklo was the first body other than a giant planet known to have a ring system7, and the Centaur Chiron was later found to possess something similar to Chariklo’s rings8,9. Here we report observations from multiple Earth-based observatories of Haumea passing in front of a distant star (a multi-stellar chordal occultation). Secondary events observed around the main body of Haumea are consistent with the presence of a ring with an opacity of 0.5, width of 70 kilometres and radius of about 2,287 kilometres. The ring is coplanar with both Haumea’s equator and the orbit of its satellite Hi‘iaka. The radius of the ring places it close to the 3:1 mean-motion resonance with Haumea’s spin—period—that is, Haumea rotates three times on its axis in the time that a ring particle completes one revolution. The occultation by the main body provides an instantaneous elliptical projected shape with axes of about 1,704 kilometres and 1,138 kilometres. Combined with rotational light curves, the occultation constrains the three-dimensional orientation of Haumea and its triaxial shape, which is inconsistent with a homogeneous body in hydrostatic equilibrium. Haumea’s largest axis is at least 2,322 kilometres, larger than previously thought, implying an upper limit for its density of 1,885 kilograms per cubic metre and a geometric albedo of 0.51, both smaller than previous estimates4,10,11. In addition, this estimate of the density of Haumea is closer to that of Pluto than are previous estimates, in line with expectations. No global nitrogen- or methane-dominated atmosphere was detected.

Within our programme of physical characterization of trans-Neptunian objects (TNOs), we predicted an occultation of the star URAT1 533–182543 by the dwarf planet (136108) Haumea and arranged observations as explained in Methods. Positive occultation detections were obtained on 21 January 2017, from twelve telescopes at ten different observatories. The instruments and the main features of each station are listed in Table 1.

As detailed in Methods (see also Fig. 1), the light curves (the normalized flux from the star plus Haumea versus time) show deep
drops caused by Haumea near the predicted time (around 3:09 UT). Because the drops are abrupt, Haumea must lack a global Pluto-like atmosphere. An upper limit on the surface pressure of a nitrogen- or methane-dominated atmosphere is determined to be 15 nbar and 50 nbar, respectively, at the 3σ level.

Square-well fits to the drops provide the times of star disappearance and reappearance at each site. Those times define an occulder chord for each site, and an elliptical fit to the extremities of the chord provides the instantaneous limb of Haumea, with values of 1,704 ± 4 km and 1,138 ± 26 km for the major and minor axes of the ellipse (Fig. 2). The position angle of the minor axis is −76.3° ± 1.2°.

In addition to the main occultation, there are brief dimmings before and after the main event. These dips are abrupt, Haumea must lack a global Pluto-like atmosphere. An upper limit on the surface pressure of a nitrogen- or methane-dominated atmosphere is determined to be 15 nbar and 50 nbar, respectively, at the 3σ level.

The table shows the observing sites from which the most relevant observations were obtained, the main parameters of the observations for each site and the derived disappearance (ingress) and reappearance (egress) times of the star caused by the central body, using the square-well model fits in Fig. 1. The cycle times are the times between consecutive exposures. At Wendelstein Observatory and Konkoly Observatory, two different telescopes were used; hence there are 12 detections of the occultation from 10 different sites. Weather was clear at all of the stations except at the Bavarian Public Observatory (Munich), where intermittent clouds were present.

*The occultation by the main body of Haumea was not detectable from Mount Agliate; only ring events were detected. See Methods and Extended Data Table 2.

Table 1 | Details of the observations on 21 January 2017

| Site                              | Coordinates       | Telescope aperture, filter and observer | Detector/instrument, exposure time and cycle time | Ingress and egress times (UT) |
|----------------------------------|-------------------|----------------------------------------|---------------------------------------------------|-------------------------------|
| Skalnate Pleso Observatory, Slovakia (S) | 49° 11' 21.8" N   | 1.3 m                                  | Moravian G4-9000                                  | 3:08:26.79 ± 0.96             |
|                                  | 20° 14' 02.1" E   | No filter                              |                                                   |                               |
|                                  | 1.826 m           | R.K.                                   |                                                   |                               |
| Konkoly Observatory, Hungary (K)  | 47° 55' 01.6" N   | 1.0 m                                  | Andor iXon-888                                    | 3:08:20.3 ± 0.2               |
|                                  | 19° 53' 41.5" E   | No filter                              |                                                   |                               |
|                                  | 935 m             | A.P.                                   |                                                   |                               |
| Konkoly Observatory, Hungary (K)  | 47° 55' 01.6" N   | 0.6 m                                  | Apogee Alfa U16HC                                  | 3:08:19.5 ± 0.8               |
|                                  | 19° 53' 41.5" E   | No filter                              |                                                   |                               |
|                                  | 935 m             | A.P.                                   |                                                   | 3:10:16.4 ± 1.3               |
| Ondrejov Observatory, Czech Republic (O) | 49° 54' 32.6" N   | 0.65 m                                 | Moravian G2-3200                                  | 3:08:29.2 ± 0.8               |
|                                  | 14° 46' 53.3" E   | No filter                              |                                                   |                               |
|                                  | 526 m             | K.H.                                   |                                                   |                               |
| Crni Vrh Observatory, Slovenia (CV)| 45° 56' 45.0" N   | 0.6 m                                  | Apogee Alfa U9000HC                                | 3:07:54 ± 8                   |
|                                  | 14° 04' 15.9" E   | Clear                                  |                                                   | 3:09:57 ± 10                  |
|                                  | 713 m             | H.M.                                   |                                                   |                               |
|                                  |                   | 315 s                                  |                                                   |                               |
| Wendelstein Observatory, Germany (W)| 47° 42' 13.6" N   | 2.0 m                                  | WWFI                                              | 3:07:29.7 ± 2.8               |
|                                  | 12° 00' 00.8" E   | r'                                     |                                                   | 3:09:34.1 ± 0.5               |
|                                  | 1.838 m           | C.R.                                   |                                                   |                               |
| Wendelstein Observatory, Germany (W)| 47° 42' 13.6" N   | 0.4 m                                  | SBIG ST10-XME                                     | 3:08:18.8 ± 6                 |
|                                  | 12° 00' 00.8" E   | r'                                     |                                                   | 3:09:38.6 ± 6                 |
|                                  | 1.838 m           | C.R.                                   |                                                   |                               |
| Bavarian Public Observatory, Munich, Germany (M)| 48° 07' 19.2" N | 0.8 m                                  | ATIK 314L-                                       | 3:08:30.0 ± 3.3               |
|                                  | 11° 36' 25.2" N   | No filter                              |                                                   |                               |
|                                  | 538 m             | B.G.                                   |                                                   |                               |
|                                  |                   | 30 s                                   |                                                   |                               |
| Asiago Observatory, Cima Ekar, Italy (As)| 45° 50' 54.9" N | 1.82 m                                 | AFOSC                                             | 3:08:20.17 ± 0.08             |
|                                  | 11° 34' 08.4" E   | No filter                              |                                                   | 3:09:13.27 ± 1.5              |
|                                  | 1,376 m           | V.G.                                   |                                                   |                               |
|                                  |                   | 5.026 s                                |                                                   |                               |
| San Marcello Pistoiese Observatory, Italy (SMP)| 44° 03' 51.0" N | 0.6 m                                  | Apogee Alfa U6                                    | 3:08:22.9 ± 0.9               |
|                                  | 10° 48' 14.0" N   | No filter                              |                                                   | 3:08:42.8 ± 0.9               |
|                                  | 965 m             | P.Bacci, M.M., L.N. and L.M.           |                                                   |                               |
|                                  |                   | 11.877 s                               |                                                   |                               |
| Lajatico Astronomical Centre, Italy (L)| 43° 25' 44.7" N | 0.5 m                                  | Moravian G3-1000                                  | 3:08:19.9 ± 1.4               |
|                                  | 10° 43' 01.2" E   | No filter                              |                                                   | 3:08:34.3 ± 1.4               |
|                                  | 433 m             | M.B. F. Martinelli, G.S.               |                                                   |                               |
|                                  |                   | 16.254 s                               |                                                   |                               |
| Mount Agliate Observatory, Italy (Ag)| 43° 59' 43.1" N | 0.5 m                                  | FLI proline 4710                                  | 3:08:20.17 ± 0.08             |
|                                  | 10° 30' 53.8" E   | No filter                              |                                                   |                               |
|                                  | 758 m             | F.C.                                   |                                                   |                               |
|                                  |                   | 15 s                                   |                                                   |                               |
|                                  |                   | 16.254 s                               |                                                   |                               |

The values of \( H_c \) that rotates around the axis \( p \) = ± 0.2°, which corresponds to an edge-on geometry. A ring particle orbiting a triaxial body with semi-axes \( a > b > c \) that rotates around the axis \( c \) has its average angular momentum \( H_c \) along \( c \) conserved. In this case, the state of least energy for a collisional, dissipative disk with constant \( H_c \) is an equatorial ring. Therefore, Haumea’s equator should also be observed under the angle 13.8°, which is consistent with the high amplitude of its rotational light curve, which requires low values of \( B \) (ref. 1). The values of \( P_{\text{ring}} \) and \( B_{\text{ring}} \) provide two possible solutions for the ring pole, with |2000 equatorial coordinates \((\alpha_p, \delta_p) = (285.1° ± 0.5°, −10.6° ± 1.2°)\) (solution 1) and \((\alpha_p, \delta_p) = (312.3° ± 0.3°, −18.6° ± 1.2°)\) (solution 2). Solution 1 is preferred, because it is consistent with the long-term photometric behaviour of Haumea and because it is coincident, to within error bars, with the orbital pole position of Haumea’s main satellite, Hi‘iaka, \((\alpha_p, \delta_p) = (283.0° ± 0.2°, −10.6° ± 0.7°)\) (ref. 14). In that context, both the ring and Hi‘iaka would lie in Haumea’s equatorial plane. At about 2,287 km from Haumea’s centre, the ring is within the Roche limit of a fluid-like satellite, which corresponds to about 4,400 km for a spherical Haumea (using a density of 1,885 kg m⁻³ for the primary and a density of 500 kg m⁻³ for the satellite). When the elongated shape of Haumea is considered, the Roche limit is even further out. Hence, the ring is close enough to Haumea that accretion cannot proceed to form a satellite. The ring is close to the 3:1 spin–orbit resonance with Haumea, a ring particle undergoing one revolution while Haumea completes three rotations. This resonance occurs at 2,285 ± 8 km (see Methods). More knowledge of the ring orbit and of the internal structure of Haumea (which may be not homogeneous, see below) will be required to show whether this proximity is coincidental or the ring is actually trapped into...
this resonance, and if the latter, for what reason. However, answering these questions remains out of reach of the present work.

Another important property of Haumea is its geometric albedo ($p_V$), which can be determined using its projected area, as derived from the occultation, and its absolute magnitude\textsuperscript{15}. We find a geometric albedo $p_V = 0.51 \pm 0.02$, which is considerably smaller than the values of 0.7–0.75 and 0.804\textsuperscript{15,16} derived from the latest combination of Herschel and Spitzer thermal measurements\textsuperscript{15,16}. The geometric albedo should be even smaller if the contributions of the satellites and the ring to the absolute magnitude are larger than the 13.5% used here (see Methods).

Because Haumea is thought to have a triaxial ellipsoid shape\textsuperscript{1,17,18} with semi-axes $a > b > c$, the occultation alone cannot provide its three-dimensional shape unless we use additional information from the rotational light curve. From measurements performed in the days before and after the occultation, and given that we know Haumea’s rotation period with high precision\textsuperscript{16}, we determined the rotational phase at the occultation time. It turns out that Haumea was at its absolute brightness minimum, which means that the projected area of the body was at its minimum during the occultation.

The magnitude change from minimum to maximum absolute brightness determined from the Hubble Space Telescope is 0.32 mag (using images that separated Haumea and Hi’iaka\textsuperscript{19}). Using equation (5) in ref. 19 together with the aspect angle in 2009 (when the observations were taken\textsuperscript{17}) and the occultation eclipse parameters, we derive the following values for the semi-axes of the ellipsoid: $a = 1,161 \pm 30\,\text{km}$, $b = 852 \pm 4\,\text{km}$ and $c = 513 \pm 16\,\text{km}$ (see Methods). The resulting density of Haumea, using its known mass\textsuperscript{20}, is $1.885 \pm 0.05\,\text{kg}\,\text{m}^{-3}$, and its volume-equivalent diameter is $1,595 \pm 11\,\text{km}$. This diameter is determined under the assumption that the ring does not contribute to the total brightness. For an upper limit of 5% contribution (see Methods), the real amplitude of the rotational light curve increases, and hence the a semi-axis increases too. The volume-equivalent diameter in this case is $1,632\,\text{km}$ and the density is $1.757\,\text{kg}\,\text{m}^{-3}$. These two densities are considerably smaller than the lower limit of $2,600\,\text{kg}\,\text{m}^{-3}$ based on the figures of hydrostatic equilibrium, or on mass and previous volume determinations\textsuperscript{1}. A value in the range 1.885–1.757 kg m\textsuperscript{-3} is far more in line with the density of other large TNOs and in agreement with the trend of increasing density versus size (see, for example, supplementary information in ref. 5, and refs 21 and 22). We also note that the axial ratios derived from the occultation are not consistent with those expected from the hydrostatic equilibrium figures of a homogeneous body\textsuperscript{23} for the known rotation rate and the derived density. It has previously been hypothesized\textsuperscript{24} that the density of Haumea could be much smaller than the minimum value of $2,600\,\text{kg}\,\text{m}^{-3}$ reported previously, if granular physics is used to model the shape of the body instead of the simplifying assumption of fluid behaviour. From figure 4 of ref. 25, we determine an approximate angle of friction of between 10° and 15° for Haumea given the $c/a$ ratio of about 0.4 that we determined here. For reference, the maximum angle of friction of solid rocks on Earth is 45° and that of a fluid is 0°. Also, differentiation and other effects may have an important role in determining the final shape\textsuperscript{26}.

Chariklo, a body of around 250 km in diameter with a Centaur orbit (between the orbits of Jupiter and Neptune), was the first Solar System object other than the giant planets found to have a ring system\textsuperscript{27}. Shortly after that discovery, similar occultation features that resembled those from Chariklo’s rings were found on Chiron\textsuperscript{28,29}, another Centaur. These discoveries directed our attention to Centaurs and phenomenology related to them to explain our unexpected findings. The discovery of
Hypothesis of an inhomogeneous ring unlikely. The two ellipses around orbital pole position of Hi'iaka 14 implies a sub-observer elevation of fact that Hi'iaka P Haumea's apparent minor axis P B times of 5.5 s were long compared to the integration time of 10 s. Also, the high signal-to-noise ratio of the data) either because the ring is not homogeneous or because its egress is lost in the readout time (marked here in green). The latter is the most likely explanation because the readout homogeneity intervals for the midtimes of the secondary events at Mount Agliale (Ag), Lajatico (L), San Marcello (S), Pistoiese and Lajatico are not observed because they are blocked by the high signal-to-noise ratio. The ring egresses at Wendelstein, Asiago, San Marcello segments show the 1σ Haumea's ring geometry.

Implications, such as rings being possibly common also in the trans-Neptunian region. VIII. Combined Herschel PACS and SPIRE observations of nine bright targets at 70–500 μm. Astron. Astrophys. 555, A15 (2013).

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METHODS

Occultation predictions. The occultation was predicted in late 2015 by using the URAT1 star catalogue and several ephemeris sources for Haumea. Because the star involved in the occultation (URAT1 533–182543) was sufficiently bright (mag ≈ 17.7), the event had the potential to be detectable from numerous sites. The initial predictions based on a JPL orbit (obtained at the JPL horizons website; http://ssd.jpl.nasa.gov/horizons.cgi) put the shadow path slightly outside Earth. Other ephemeris sources such as Astorb (ftp://ftp.lowell.edu/pub/elgh/astorb.html) and NIMA7 were more favourable, giving rise to shadow paths well within Earth. The scatter in the predictions, owing to the uncertainty in Haumea's orbit, was of the order of 300 milliarcseconds (mas). Given that Haumea's angular diameter was expected to be much smaller than that, refined predictions were needed to make sure that a detection could be made. Besides, the presence of a large satellite (Hi'iaka) orbiting Haumea could cause an astrometric wobble similar to that detected in the system of Orcus and its satellite Vanth due to the photocentre oscillation around the barycentre of the system.

Hence, we decided to carry out a detailed astrometric monitoring of Haumea. More than 1,000 measurements of Haumea's position were obtained with the 0.77-m f/3 La Hita telescope from 1 April to 4 July 2016 using a 4,096 × 4,096 CCD (charge-coupled device) camera. The unfiltered images were taken on a daily basis (weather and moon permitting) when Haumea was near culmination to avoid possible differential chromatic refraction (DCR) problems as much as possible. The instrument, the image processing and the methodology were the same as those used for the prediction of the stellar occultation by Makemake. The analysis of the data resulted in a shadow path favourable for locations in a wide region of Earth. Hence, this encouraged further work. Once the GaiaDR1 catalogue was released we improved our prediction with new coordinates of the occultation star by combining the position (epoch 2015.0) with the information on position and proper motions from URAT1 at its 2013.669 epoch and from other catalogues.

The final star coordinates (J2000) that we derived for the occultation epoch (2017.058) were right ascension α = 14 h 12 min 03.2034 s and declination δ = +16° 33′ 58.642″. After the occultation, the HSOY catalogue has become available, which provides coordinates and proper motions of GaiaDR1 stars matched with PPMX1 stars. From this catalogue, the J2000 coordinates for epoch 2017.058 turn out to be α = 14 h 12 min 03.2034 s, δ = +16° 33′ 58.647″, which agree completely in right ascension and differ by only 4 mas in declination.

Once the GaiaDR1 catalogue became available in September 2016 we also reid the Haumea astrometry from the entire La Hita 0.77-m telescope dataset with respect to GaiaDR1. Owing to the higher accuracy of GaiaDR1 with respect to previous catalogues of similar depth, the resulting astrometry showed a clear occultation of the residuals to the JPL orbit with respect to the measurements (observed — calculated) due to the presence of the satellite Hi'iaka. A Lomb periodogram of the residuals in declination showed its strongest peak at a significant periodicity of 49.5 ± 0.9 days, which coincides with the known orbital period of Hi'iaka (49.462 ± 0.083 days). A sinusoidal fit to the residuals (Extended Data Fig. 1) using the orbital period of Hi'iaka had a maximum when the theoretical position of Hi'iaka was at its northernmost position with respect to Haumea, and the minimum of the fit corresponded to the southernmost position of the satellite Hi'iaka. Hence we verified that the oscillation was indeed correlated with the theoretical positions of Hi'iaka. For the theoretical computations of the Hi'iaka orbit we used the miriade ephemeris service (http://vo.imcce.fr/webservices/miriade/).

With that information we could already make a reliable prediction of the occultation for 21 January 2017 that indicated a favourable shadow path for central Europe. The resulting offsets with respect to JPL#81 orbit (with planetary ephemeris version DE431) were 174 mas and 73 mas in ncosδ and in δ, respectively. This represented the offset of the barycentre of Haumea's system with respect to the JPL#81 ephemerides. In early December 2016 we again took images of Haumea, and astronomically solved them with respect to the GaiaDR1 catalogue. This time we used several larger telescopes (the Sierra Nevada Observatory 1.5-m telescope, the Calar Alto Observatory 1.2-m telescope, the Pic du Midi Observatory 1-m telescope, the 2-m Liverpool telescope and the 2.5-m Nordic Optical telescope to obtain observations of Haumea in R band). We determined the offsets of the astrometric measurements with respect to JPL ephemerides (observed — computed). Then we performed a correlation analysis of the offsets with respect to the computed theoretical positions of the satellite Hi'iaka and found offsets in α and δ for the position of the barycentre of the Haumea system with respect to the ephemerides. These offsets were determined from linear fits and are 1.76 ± 0.6 mas in ncosδ() and 7.3 ± 11 mas in δ with respect to the JPL#81 orbit. The errors were determined from the uncertainties in the parameters of the linear fits. These offsets were in perfect agreement with those calculated with the large La Hita dataset. The Spearman correlation coefficients were 0.91 and 0.88 for the right ascension and declination residuals, respectively.

On the other hand, we determined the distance of Haumea with respect to the barycentre using 1.232/(1 − r), where 1.232 is the separation of Hi'iaka with respect to Haumea in milliarcseconds and r is the mass ratio of Haumea to Hi'iaka. That mass ratio was thought to be about 200, assuming similar albedos for Haumea and Hi'iaka (or even higher for Hi'iaka, given the depth of the water ice feature as shown in ref. 31). Projected in the plane of the sky, the offset position of Haumea on 21 January 2017 with respect to the barycentre was then calculated to be −6 mas in declination and 2 mas in ncosδ. The predicted shadow path was favourable for the Haumea occultation campaign with observing sites from Spain to Turkey to maximize the chances of success and to compensate for possible systematic errors that could have not been accounted for.

A map of the final shadow path on Earth with the sites that played the key parts in the observations is shown in Extended Data Fig. 2. The centre of Haumea from the occultation was 17 mas and 16 mas away from the prediction, in ncosδ and δ, respectively. This translates into a difference of 409 km in the centerline of the shadow path and 55 s in time with respect to the prediction.

Occultation observations. Sequences of CCD images were acquired at each observing site listed in Table 1. At Wendelstein, a red r sloan filter was used, while all the other observatories used no filters to maximize the signal-to-noise ratio. Except for the Konkoly 1-m telescope observations, all of the image sequences had interruptions due to the non-negligible readout time of the cameras.

From the sequences of CCD images obtained at each telescope (and after standard dark-subtraction and flatfielding correction), light curves were constructed by carrying out synthetic aperture photometry of the occultation star (blended with Haumea) with respect to reference stars in the field of view. The synthetic aperture measurements were made using DAOPHOT routines and searching for the optimum aperture to minimize the scatter of the photometry. The photometry was performed relative to reference stars in the images so that small transparency fluctuations or seeing variations could be monitored and compensated for. The timing information was extracted from the time in the fits headers of the images. The time tagging accuracy at the different observatories (time tagging was done by synchronizing the controlling computers with NTP time servers) is estimated to be 0.1 s on average. The main parameters of the star are shown in Extended Data Table 1. The brightness of the star was similar to that of Haumea, so at the time of the occultation we expected a brightness change of around 30% in the Haumea + star blended source. The resulting light curves (photon flux relative to the average value, versus time) are shown in Fig. 1.

The observations at Crn Vrh consisted of drifted images with 300 s of exposure time, tracked at a speed of 40″ per minute in the north–south direction. Hence, aperture photometry could not be made. The detailed analysis procedure for this dataset is explained in Methods section ‘Analysis of the Crn Vrh images’.

Limb fit to the occultation chords. Square-well fits to the occultation profiles were performed to accurately determine the times of star disappearance and reappearance for each observatory (Table 1), except for Crn Vrh, for which a special technique was needed as explained in Methods section ‘Analysis of the Crn Vrh images’. The methodology to fit square wells was the same as that in other work on stellar occultations5,23 by TNOs. The main parameters of the model are the depth of the square well, and the disappearance and reappearance times of the occultation. The uncertainties in the retrieved parameters were obtained from a grid search in the parameter space. Acceptable values were those that gave a χ2 within χ2min + 1. The uncertainties are listed in Table 1. The errors from the time tagging accuracy were an order of magnitude smaller than the uncertainties arising from the fits. From the fitted times at the different sites, we can generate chords in the projected plane of the sky. We fitted an elliptical limb to the extremities of the chords by minimizing a χ2 function:

\[ \chi^2 = \sum \left( \frac{r_{\text{fit,obs}} - r_{\text{cal,fit}}}{\sigma_{r}} \right)^2 \]

where r is the radius from the centre of the ellipse (f, g), r' means calculated and 'obs' means observed; σr are the errors of the extremities, which were derived from the errors in the retrieved ingress and egress times (using the known speed of Haumea), and N is the number of extremities. The retrieved a and b' parameters (semi-axes of the fitted ellipse, not to be confused with the semi-axes of the triaxial ellipsoid) were then converted to milliarcseconds into length in kilometres by using the known distance of Haumea from Earth (50 4874 AU). This is the same procedure followed in other stellar occultation studies of TNOs4,23. The parameters of the ellipse fit were 1.704 ± 4 km, 1.138 ± 26 km and Pobi = −76.3 ± 1.2°. The fit used 9 occulting chords, providing 18 data points along the limb, and returned the best-fitting value for χ2min = 18.6. This value corresponds to a χ2 per degree of freedom of 1.43, because we have 5 free parameters, which means that the fit is satisfactory.
Upper limit on the pressure of a putative atmosphere. Global atmospheres of the type seen in Pluto and other Solar System bodies cause a gradual star disappearance during occultations as well as a gradual reappearance. Upper limits on the pressure of a putative nitrogen-dominated or methane-dominated Pluto-like atmosphere can be derived from the occultation profiles; see below. Nitrogen and methane are the volatile ices that can sublimate at the distances from the sun at which Haumea is (50.593 au). Even though there is no spectroscopic evidence of N₂ or CH₄ ices on Haumea’s surface in substantial amounts, their presence below the surface cannot be completely discarded.

Here we use the best available dataset—the Asiago light curve—to derive Haumea’s atmospheric upper limits (Fig. 1). From Haumea’s mass of (4.006 ± 0.04) × 10²¹ kg (ref. 20) and assuming that the body itself is in hydrostatic equilibrium we derive an average surface gravity of 0.39 m s⁻².

We consider first a pure N₂ isothermal atmosphere in thermal balance with a surface temperature of 40 K (ref. 16). This provides a vertical density profile from which a ray-tracing code calculates synthetic light curves, once a surface pressure \( p_{\text{surf}} \) has been prescribed (see refs 4 and 5 for details). We define a \( \chi^2 \) function in the same way as in equation (1), except that now \( p_{\text{surf}} \) is the adjusted parameter. We find that \( \chi^2 \) is minimum for \( p_{\text{surf}} = 0 \) (no atmosphere) and that it reaches \( \chi^2_{\text{min}} = 1 \) for \( p_{\text{surf}} = 3 \) bar, which sets the 1σ-level upper limit for a N₂ atmosphere. At 3σ the upper limit is 15 bar. In Extended Data Fig. 3, we show the effect that a N₂ isothermal atmosphere would have on the observations.

A CH₄ atmosphere would be more difficult to detect using our dataset. This stems from the fact that near-infrared heating of methane would cause a thermal profile starting from a typical surface temperature of 40 K, then ramping up to typically 100 K in a few-kilometre-thick stratosphere (see discussion in ref. 5). Our dataset lacks sufficient spatial resolution to resolve such a thin layer, so a less constraining upper limit of \( p_{\text{surf}}(\text{CH}_4) = 10 \) bar (1σ-level) is derived from our observations. At 3σ the upper limit is 50 bar.

In any case, the upper limits are three orders of magnitude below Pluto’s atmospheric pressure, meaning that if a global atmosphere exists on Haumea it is extremely tenuous.

Ring fit to the secondary events. Apart from the occultations by the main body, the light curves reveal brief dimmings from most of the sites before and/or after the main event. The timings of these events (see Extended Data Table 2) were extracted by fitting square–well ring profiles to the short events, in the same way as for Charliko (ref. 7). However, the only resolved profiles come from the Konkoly 1-m telescope (Fig. 1). At that station, we derive a radial width (in the ring plane) of \( W_{\text{ring}} \approx 74 \) km at ingress and \( W_{\text{ring}} \approx 44 \) km at egress, with respective apparent opacities (along the line of sight) of \( p^r = 0.55 \) and \( p^r = 0.56 \). This implies so-called equivalent widths \( W_{\text{equiv}} = W_{\text{ring}}^r \) of 41 km and 25 km, respectively; a measure of the radially integrated amount of material confined in the ring. Note that the apparent opacity is related to the apparent optical depth through \( \tau^r = -\ln(1 - p^r) \).

Converting the apparent optical depth into a ring-normal optical depth \( \tau^f \) is not straightforward, because the conversion depends on whether the ring is mono- or poly-layer (and it can be neither, as these are idealized cases); it is complicated further by diffraction by individual ring particles.

For the rest of the sites, the ring profiles are not resolved and large readout times between integration intervals prevent a full recording of each event. Consequently, we used a simple model with a uniform ring of width of 70 km and apparent opacity between integration intervals prevent a full recording of each event. Consequently, a straightforward, because the conversion depends on whether the ring is mono-layer, this implies a ring radius of \( b = 1.161 \) km, \( b = 852 \) km and \( c = 513 \) km (see Methods section ‘Three-dimensional shape and density of Haumea’). The ring cannot contribute more than 5% of the flux because in that case the rate of change of the amplitude is too steep to be compatible with the observations (Extended Data Fig. 5b). In addition, the pole solution (312.3°, –18.6°) can be discarded as it produces a model that is out of phase compared to the observations of the amplitude of the light curve.

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Regarding the origin of the ring, different mechanisms are possible. Impacts on Haumea might launch material in orbit around it, with some material ending up as a ring inside the Roche limit, possibly concentrated in particularly stable regions such as a spin–orbit resonance or near a shepherding satellite. Alternatively, the tidal disruption or collisional disruption of a previously existing satellite could generate a debris disk that would then stay in orbit. Several possible mechanisms for ring formation have been discussed for the ring systems found around Chiron28,29 and Chiron3, some of which could also apply to Haumea. Other scenarios that invoke cometary activity as the source of rings40 do not apply to Haumea because such activity is unobservable for a remote and large TNO. In any case, the ring formation process is probably related to that which formed Hi’iaka and Namaka, and perhaps the orbitally related Haumea family42.

Some models43 include the possibility that rings can be found only between 8 au and 20 au from the Sun. This is in principle ruled out by the detection of Haumea’s ring, currently situated at a heliocentric distance of more than 50 au, although it cannot be disregarded that Haumea could have formed much closer in and migrated to its current position with the ring already formed.

**Geometric albedo of Haumea.** If the projected size of a Solar System body (A) and its brightness are known, we can determine the geometric albedo by using

\[ P_l = \frac{4}{\pi} \frac{V_{\text{max}} - V_{\text{H}}} {A} \]

where \( V_{\text{max}} \) is the magnitude of the Sun (\( m_v = -26.74 \)) and \( V_H \) is the instantaneous absolute magnitude, which can be obtained from the rotationally averaged absolute magnitude \( (V_H) \) of Haumea main body. The value of \( (V_H) \) determined from the ground includes the contribution of the ring and the satellites Hi’iaka and Namaka, which should be discounted if we want to compute the true geometric albedo of the main body using the effective diameter or projected area of the occultation. The value of \( (V_H) \) of the Haumea system determined from ground-based observations15 is 0.428 ± 0.011 mag. However, this absolute magnitude corresponds to 2005 and we should use the value derived in 2017, plotted in Extended Data Fig. 5, which is brighter by 0.07 mag. The brightness contribution of the ring to the total brightness of the Haumea system (main body + ring) was assessed to be almost negligible in the previous section. Hence, if we subtract a contribution of 2.5% from the brightness to the \( (V_H) \) measurements of the Haumea system and an approximately 11% contribution from Hi’iaka44 and Namaka, then the correct \( V_H \) value for Haumea’s main body at the time of the occultation becomes 0.35 ± 0.14 + 0.32/2 (we had to add at least 0.32/2 mag because Haumea was at its rotational minimum at the time of the occultation, as explained in Methods section ‘Three-dimensional shape and density of Haumea’). The resulting geometric albedo, inserting the area \( A \) from the occultation, would be 0.51, which is much smaller than the most recently determined value of 0.804 ± 0.062 derived on the basis of Herschel thermal measurements combined with Spitzer data45. Previous modelling of Herschel observations16 resulted in an albedo of 0.7–0.75, still much higher than the value from the occultation. The main reason for the difference comes from the fact that the occultation results give rise to a larger body than estimated previously, possibly as a result of different beaming parameters or phase integrals, or deficiencies in the modified thermal models when applied to very elongated TNOs such as Haumea. Thermal models for spherical bodies systematically underestimate the diameters and overestimate the albedos of low-obliquity ellipsoidal asteroids45. This seems also applicable to TNOs. In systematical underestimate the diameters and overestimate the albedos of very elongated TNOs such as Haumea. Thermal models for spherical bodies could also depart from the classical equilibrium shapes. A non-homogeneous body can also depart from the classical equilibrium shapes. A non-homogeneous body can also depart from the classical equilibrium shapes.

**Geometric albedo of Haumea.** Using the measurements of the rotational light curve performed before and after the occultation and given that we know Haumea’s rotation period (3.915341 ± 0.000005 h) with a very small uncertainty16, we can accurately determine the rotational phase at the time of the occultation. It turns out that Haumea was at its absolute brightness minimum, which means that the projected area of the body was at its minimum. This is depicted in Extended Data Fig. 6.

Because we know the amplitude of the rotational light curve (0.32 mag; ref. 10), we can use the expression that relates the amplitude of the rotational light curve of a triaxial body43 to derive the three axes of the body:

\[ \Delta m = -2.5 \log \left( \frac{b}{a} \cos^2(\theta) + \frac{c}{a} \sin^2(\theta) \right)^{\frac{1}{2}} \]

where \( \theta \) is the angle between the semi-axes of the ellipsoid, \( \Delta m \) is the amplitude of the light curve (0.32 ± 0.006 mag) and \( \theta \) is the aspect angle, which is the complementary angle to the planetocentric latitude of the sub-Earth point (assumed to be equal to the ring opening angle, as discussed earlier). This aspect angle is thus \( \theta_0 = 90° - 13.8° = 76.2° ± 0.5° \) during the occultation in 2017, but \( \theta_0 = 90° - 6.5° = 83.5° ± 0.5° \) in 2009, when the Hubble Space Telescope observations16 were made, using the pole position of the ring given before. We use the amplitude from ref. 10 because it was determined from Hubble Space Telescope images that could resolve Haumea, Hi’iaka and Namaka, so the contribution of the satellites does not affect the photometry, contrary to the case of the ground-based observations.

Moreover, using the fact that the the \( a \) axis was directed to us during the occultation, we can relate the apparent semi-minor axis in 2017 (\( b’ = 569 \) km) to the true semi-minor axis through \( (b')^2 = \sin^2(\theta_0) + \cos^2(\theta_0) \). Combining this equation with the previous one, and using the numerical values mentioned before, we obtain

\[ a > b > c = (1,161 ± 30) \times (852 ± 2) \times (513 ± 16) \] km.

The formal error on \( a \) comes mainly from the uncertainty on \( \Delta m \). The value quoted above (±0.006) seems too optimistic to represent the oscillation due entirely to shape, so we used a more plausible value of ±0.02 due to the possible presence of albedo features on Haumea. The formal error on \( b \) comes mainly from the limb fitting (Fig. 3), because the \( a \) axis was directed to us during the occultation. Finally, the formal error on \( c \) stems directly from the uncertainty on the apparent semi-minor axis, 569 ± 13 km, which again relies on the limb fitting.

In fact, 0.32 mag is a lower limit for \( \Delta m \) because the constant contribution of the ring brightness was not accounted for. The actual amplitude of the oscillation that would be caused by Haumea alone, without ring, would be larger than 0.32 mag. However, the ring contribution is small, as explained in previous sections, and the difference in the amplitude of the light curve arising from this is expected to be small. Nevertheless, we cannot neglect the possibility that unknown satellites or additional rings could also contribute a few per cent.

The density of Haumea, using the values of \( a, b \) and \( c \) derived above and the mass determination from the occultation period of Hi’iaka20, is 1,885 ± 80 kg m\(^{-3}\). For an semi-axis larger than the nominal 1,161 km determined here, the density will be even less than 1,885 kg m\(^{-3}\). For a ring brightness of 5% (which is larger than needed to fit the absolute magnitude data), the longest axis would be 2,520 km, the volume-equivalent diameter becomes 1,632 km and the density would be 1,757 kg m\(^{-3}\). We consider this value a lower limit. Values of 1,885–1,757 kg m\(^{-3}\) are closer to the density of the rest of the known large TNOs and are in agreement with the trend of increasing density with size (see, for example, the supplementary information in ref. 5, and refs 21 and 22).

These values can be compared to the limits imposed by the hydrostatic equilibrium of a Jacobi ellipsoid23. In this case, the parameter \( \gamma = \gamma(\pi G \rho) \) must be bounded by 0.284 and 0.374 (\( \omega \) being the spin frequency of the body, \( G \) the gravitational constant and \( \rho \) the density). Using a rotation period of 3.915341 h for Haumea, we obtain the condition 2,530 km m\(^{-3}\) < \( < p < 3,340,340 \) km m\(^{-3}\). This is far from our upper limit of 1,885 kg m\(^{-3}\) kg m\(^{-3}\), showing that Haumea cannot be a homogeneous ellipsoid in hydrostatic equilibrium.

The axis ratios \( b/a = 0.73 \) and \( c/a = 0.44 \) are consistent with those of a Jacobi ellipsoid with \( \gamma(\pi G \rho) = 0.35 \), but the density required by that solution (2,700 kg m\(^{-3}\)) is not consistent with our measurements. It has previously been noted46 that Haumea’s shape might not be that of a fluid equilibrium Jacobi body if granular physics is used to model the shape instead of using the simple assumption of fluid behaviour. It was also concluded44 that the density of Haumea could be much smaller than the minimum of 2,600 kg m\(^{-3}\) reported in the literature10,16. For an ellipsoidal body with \( b = (a + c)/2 \), we can determine an angle of friction of between 10° and 15° from figure 4 of ref. 25 for a density of 1,885 kg m\(^{-3}\). A non-homogeneous body can also depart from the classical equilibrium shapes. Differentiation can be expected in large bodies such as Haumea, but it remains to be seen whether feasible mass concentrations towards the nucleus can explain its current shape and density. **Analysis of the Crni Vrh images.** Given that the images were acquired while the telescope was guided at a sidereal rate and moving at a speed of 40 arcsec per second in the north–south direction, the resulting images show trailed stars. By using 300 s of exposure time and reading out the CCD in 15 s, the percentage of ‘deadtime’ was only around 5%. This comes at the expense of increasing the background noise considerably. The images were dark-subtracted and flatfielded following standard procedures. To analyse the tail of the occultation star plus Haumea (both blended in a single trail), we took line profiles along the centre (and most intense) part of the trail in the different images. Given the known drift of the telescope, we can translate the pixel along the profile to time after the integration. The pixel scale was 1.4 arcsec per pixel. Plots of these line profiles are shown in Extended Data Fig. 7 for images before and during the main occultation event.
The smoothed line profile of the trail in the image at the time of the occultation shows a clear drop in intensity at an approximate time indicated by the dashed vertical line in Extended Data Fig. 7. This corresponds to the time when the star disappeared as a result of the occultation. The intensity remains low for the rest of the integration, which means that the star did not reappear while the image was being taken. We can thus determine a disappearance time and estimate that the reappearance probably took place while the CCD camera was being readout.

In addition, from the elliptical fit to the occultation chords of the rest of the sites, the reappearance time at Crni Vrh is expected to have happened approximately at the time of the readout. The timings derived in this way are shown in Table 1. Even though the time uncertainties are large and difficult to estimate, the data still provide valid information.

**Data and code availability.** All relevant data are available from the corresponding author on request. We have opted not to make our codes available as we cannot guarantee their correct performance on different computing platforms.

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Extended Data Figure 1 | Declination residuals of Haumea astrometry. The plus symbols show the declination residuals of the observed position of the photocentre of Haumea’s system with respect to the theoretical position in declination, from JPL#81 ephemerides. The residuals are shown versus the date of observation. All of the observations were obtained with the La Hita 0.77-m telescope, as explained in Methods. The thin solid line represents a sinusoidal fit to the residuals, with the period determined from a periodogram analysis that is coincident with the orbital period of the moon Hi’iaka. Outlier values have not been removed. In right ascension we did not detect an oscillating behaviour of the residuals because the orbit Hi’iaka does not extend as much as in declination and the quality of the data was not good enough to show the periodicity.
Extended Data Figure 2 | Map of Earth showing the locations of the observatories that recorded the occultation (green dots). The solid lines mark the limits of the shadow path. Mount Agliale is indicated in blue because the occultation by the main body was not positive there, but the occultation by the ring was detected. The dashed line denotes the centre of the shadow path. Note that Munich corresponds to the location of the Bavarian Public Observatory. The complete names of the observatories can be found in Table 1. The red marks at Trebur and Valle D'Aosta observatories indicate the two closest sites to the shadow path that recorded a negative occultation. The coordinates of Trebur observatory are 49° 55′ 31.5″ N, 8° 24′ 40.6″ E and the coordinates of Valle D'Aosta observatory are 45° 47′ 22″ N and 7° 28′ 42″ E. The shadow motion is from the bottom to the top of the figure.
Extended Data Figure 3 | Upper limit on Haumea's N₂ atmosphere. The black filled circles show the normalized flux from the star plus Haumea, as observed from the Asiago station, which is the one that provided the highest signal-to-noise ratio and enough time resolution to look for a faint atmosphere. They combine ingress and egress data and are plotted against the distance perpendicular to the local Haumea limb, as given by the solution shown in Fig. 2. The horizontal bars associated with each data point indicate the distance interval corresponding to the integration times of each point. The red line shows an example light curve obtained with an isothermal N₂ atmosphere at $T = 40$ K and with surface pressure $p_{\text{surf}} = 15$ nbar (at $3\sigma$-level upper limit for better illustration, because the $1\sigma$-level of 3 nbar would be difficult to notice). The red open circles show the expected flux at each data point after convolution with the finite integration point.
Extended Data Figure 4 | Upper part of the ring. An expanded view of Fig. 3 showing in more detail the events along the upper part of the ring. The best fitting mean ring radius $a_{\text{ring}} = 2,287.75$ km is drawn as a solid curve. The grey area shows the full extension of a semi-transparent 70-km-wide ring that is consistent with the twelve secondary events shown in Fig. 3. The lengths of the red segments indicate the uncertainties stemming from the error bars on the ring timings.
Extended Data Figure 5 | Photometric models. 

a, Absolute V-band magnitude of the Haumea system as a function of time. Diamonds represent observations and lines are models. The cyan curve represents a model without a ring, the black curve is a model with a 70-km-wide ring and with a reflectivity of $I/F = 0.09$, similar to that of Chariklo's main ring. The ring in this model contributes approximately 2.5% of the total flux of Haumea plus Hi'iaka in 2017. The dark blue curve corresponds to a model with a wider (140 km) and brighter ($I/F = 0.36$) ring, which contributes 20% of the total brightness in 2017. This model can be discarded because it would produce a change in the amplitude of the light curve that is too rapid to be compatible with the observations (see b). 

b, Amplitude of the rotational light curve determined from the ground for the same three models as in a (using the same colour coding). The diamonds represent observations from the literature\(^1,17\) and from this work (for 2017). See Methods for further explanations. Error bars show the errors of the measurements from refs 1 and 17 and from the determination in 2017 from this work, shown in Extended Data Fig. 6.
Extended Data Figure 6 | Rotational light curve of Haumea. The relative magnitude versus rotational phase obtained two days after the occultation with the Valle D’Aosta 0.81-m telescope with no filters is shown. The rotational zero phase was established at the time of the occultation and the rotation period used was 3.915341 h. Superimposed is a fit to the observational data. As can be seen, the absolute maximum in magnitude (absolute brightness minimum) is reached at the time of the occultation (arbitrarily located at a phase of 0 here), which means that the projected area of Haumea was also at its minimum. The continuous line is a fit to the data. The peak-to-peak amplitude of the light curve is $0.25 \pm 0.02$ mag. Error bars are $1\sigma$. 

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Extended Data Figure 7 | Profiles of the trails of the occultation star in two images. **a**, Profile along a central line in the trail of the occultation star (blended with Haumea) in a drifted image taken from Crni Vrh observatory before the main occultation. On the y axis we show the light intensity along the line. The line starts 40 pixels before the beginning of the trail and ends 40 pixels after the end of the trail to show the background level and that the transition from trail to background is not easy to identify. The horizontal line marks the mean intensity of the trail. The thick line represents a profile smoothed with a 10-pixel boxcar to filter the high-frequency noise. The x axis has been translated from pixels to time using the drift speed of 40 arcsec per minute, given the known pixel scale of the telescope. The vertical dashed-dotted lines at 0 s and 300 s mark the start and end of the integration, respectively. The UT at start of exposure was 02:59:19.50. The intensity is basically constant with time. Before 0 s and after 300 s, the line profiles decay to the background level of the image because the pixels there were outside the trail. Hence, before 0 s and after 300 s, the plot does not represent the intensity of the source but the intensity of the background. **b**, Same as **a**, but from the image at the time of the occultation. The UT at the start of the exposure was 03:04:50.11. The dashed vertical line at 185 s marks the approximate moment at which the occultation begins. The smoothed curve shows that a clear drop in the signal is produced and lasts until the end of the 300-s integration. ADU, analog-to-digital unit.
Extended Data Table 1 | Data on the occulted star

| Designation       | URAT1 533-182543 GaiaDR1 1233009038221203584 |
|-------------------|-----------------------------------------------|
| Magnitude*        | B=20.88, V=17.97, R=18.000, J=15.353, H=14.791, K=14.532 |
| Diameter**        | ~0.007 mas (~0.27 km at Haumea’s distance) |
| Coordinates***    | $\alpha = 14h 12m 03s.2034, \delta = +16^\circ 33^\prime 58^\prime\prime.642$ |
| Speed****         | 13.1 km/s |

*From the NOMAD catalogue.
**Estimated from the V, B, R, J, H and K magnitudes.
***Coordinates in the J2000 equinox for epoch 2017.0575 from this work.
****Speed of Haumea with respect to the star, seen from Earth.
## Extended Data Table 2 | Timing of the secondary brief occultation events from the different observing sites on 21 January 2017

| Site Name and country | Coordinates Lat dd:mm:ss Lon dd:mm:ss | Telescope Name Aperture Filter | Detector/Instrument Exposure (s) Cycle time (s) | Mid time of event (UTC) flux standard deviation, level of ring event detection (σ) |
|----------------------|---------------------------------------|---------------------------------|--------------------------------|---------------------------------------------|
| **Skalnate Pleso Observatory -Slovakia** | 49°11′21.8″ N 20°14′02.1″ E 1826 | Astelco 1300/10400 1.3 m no filter | Moravian G4-9000 10 s 15.503 s | Ingress 3:07:04.1±5.6 0.044, 2.1 |
| **Skalnate Pleso Observatory -Slovakia** | 49°11′21.8″ N 20°14′02.1″ E 1826 | Astelco 1300/10400 1.3 m no filter | Moravian G4-9000 10 s 15.503 s | Egress* 3:11:50±2.4 0.044, n.a. |
| **Konkoly Observatory -Hungary** | 47°55′01.6″ N 19°53′41.5″ E 935 | RCC 1.0 m no filter | Andor iXon 888 1 s 1.007 s | Ingress 3:06:58.1±0.3 0.079, 4.5 |
| **Konkoly Observatory -Hungary** | 47°55′01.6″ N 19°53′41.5″ E 935 | RCC 1.0 m no filter | Andor iXon 888 1 s 1.007 s | Egress* 3:11:40±0.2 0.068, 3.5 |
| **Ondrejov Observatory -Czech Republic** | 49°54′32.6″ N 14°46′53.3″ E 526 | Ondrejov 650/2675 0.65 m no filter | Moravian G2-3200 8 s 9.721 s | Ingress 3:06:48.4±4.2 0.041, 2.5 |
| **Ondrejov Observatory -Czech Republic** | 49°54′32.6″ N 14°46′53.3″ E 526 | Ondrejov 650/2675 0.65 m no filter | Moravian G2-3200 8 s 9.721 s | Egress 3:10:51.6±3.0 0.041, 2.9 |
| **Wendelstein Observatory -Germany** | 47°42′13.6″ N 12°00′44″ E 1838 | 2.0m Fraunhofer f/7.8 2.0 m r' | WWFI** 10 s 14.536 s | Ingress 3:06:39.5±3.9 0.021, 4.9 |
| **Asiago observatory Cima Ekar -Italy** | 45°50′54.9″ N 11°34′08.4″ E 1376 | Copernico 1.82 m f/9 1.8 m no filter | AFOSC*** 2 s 5.026 s | Ingress 3:06:35.4±0.3 0.029, 8.8 |
| **S. Marcello Pistoiese observatory -Italy** | 44°03′51.0″ N 10°48′14.0″ E 965 | 0.60 f/4 0.6 m no filter | Apogee Alta U6 10 s 11.877 s | Ingress 3:06:38.8±1.5 0.039, 5.8 |
| **Lajatico Astronomical Centre -Italy** | 43°25′44.7″ N 10°43′01.2″ E 433 | RC 50 cm f/9 0.5 m no filter | Moravian G3-1000 15 s 16.254 s | Ingress 3:06:37.9±5.1 0.067, 1.6 |
| **Mount Agiiale observatory -Italy** | 43°59′43.1″ N 10°30′53.8″ E 758 | 50 cm f/4.6 0.5 m no filter | FLI proline 4710 15 s 16.724 s | Ingress 3:06:56.7±1.4 0.031, 4.5 |
| **Mount Agiiale observatory -Italy** | 43°59′43.1″ N 10°30′53.8″ E 758 | 50 cm f/4.6 0.5 m no filter | FLI proline 4710 15 s 16.724 s | Egress 3:08:15.3±4.2 0.031, 5.4 |

*The egress time at Skalnate is not a real detection of the ring; see Fig. 3.

**Information on the instrument used in this observatory can be obtained from http://www.usm.uni-muenchen.de/wendelstein/htdocs/wwfi.html.

***Information on the instrument used can be obtained at http://www.pd.astro.it/index.php/en/asiago-info-eng/who-we-are/136-asiago-eng/250-afosc.html.