The 2017 May 20 stellar occultation by the elongated centaur (95626) 2002 GZ$_{32}$

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ABSTRACT

We predicted a stellar occultation of the bright star Gaia DR1 4332852996360346368 (UCAC4 385-75921) ($m_V = 14.0$ mag) by the centaur 2002 GZ$_{32}$ for 2017 May 20. Our latest shadow path prediction was favourable to a large region in Europe. Observations were arranged in a broad region inside the nominal shadow path. Series of images were obtained with 29 telescopes throughout Europe and from six of them (five in Spain and one in Greece) we detected the occultation. This is the fourth centaur, besides Chariklo, Chiron, and Bienor, for which a multichord stellar occultation is reported. By means of an elliptical fit to the occultation chords, we obtained the limb of 2002 GZ$_{32}$ during the occultation, resulting in an ellipse with axes of 305 $\pm$ 146 km $\times$ 146 $\pm$ 8 km. From this limb, thanks to a rotational light curve obtained shortly after the occultation, we derived the geometric albedo of 2002 GZ$_{32}$ ($p_V = 0.043 \pm 0.007$) and a 3D ellipsoidal shape with axes 366 km $\times$ 306 km $\times$ 120 km. This shape is not fully consistent with a homogeneous body in hydrostatic equilibrium for the known rotation period of 2002 GZ$_{32}$. The size (albedo) obtained from the occultation is respectively smaller (greater) than that derived from the radiometric technique but compatible within error bars. No rings or debris around 2002 GZ$_{32}$ were detected from the occultation, but narrow and thin rings cannot be discarded.

Key words: methods: observational -- techniques: photometric -- occultations -- Kuiper Belt objects: individual: 2002 GZ$_{32}$.

1 INTRODUCTION

Although no official definition exists, centaurs such as (95626) 2002 GZ$_{32}$, are Solar system small bodies that orbit the Sun between the orbits of Jupiter and Neptune. Due to their large distance to the Sun, centaurs, together with trans-neptunian objects (TNOs) are thought to be the least evolved and the most pristine bodies in the Solar system, at least from the composition point of view. This means that they retained relevant information on the composition materials and physical conditions of the primitive solar nebula. Therefore, the study of these bodies reveals plenty of information on the origin and evolution of the Solar system since its initial phases. Additionally, centaurs are considered the progenitors of the short-period comets, mainly the Jupiter family comets, and it is believed that they escaped from the TNO population referred to as the scattered disc objects (SDOs; e.g. Fernández, Halé & Gallardo 2018).

The first centaur discovered was Chiron, found by Charles Kowal in 1977 (Kowal 1989). Despite the fact that more than 40 yr have elapsed since the first member of this population was discovered, our knowledge about the physical properties of the centaur population is still scarce, mainly due to the large distance, low geometric albedo and faintness of these bodies. Centaurs are thought to be mostly composed of a mixture of ices and rocks and most of the members of the population probably share similar composition to that of comets (e.g. Barucci et al. 2011).

The centaur (95626) 2002 GZ$_{32}$ was discovered on 2002 April 13 from Mauna Kea Observatory. It presents a rotational period of 5.80 $\pm$ 0.03 h with a peak-to-peak amplitude of 0.15 mag according to Dotto et al. (2008). A variable presence of water ice on the surface of this centaur has been reported (Barkume, Brown...
The 2017 May 20 stellar occultation by 2002 GZ$_{32}$

| $a$ (au) | $q$ (au) | $e$ | $i$ (deg) | $H_V^{a}$ (mag) | $P^{b}$ (h) | $\Delta m^{c}$ (mag) | $D$ (km) | $p_V$ | Spec. slope$^{d}$ | Ices$^{e}$ |
|---------|---------|-----|---------|---------------|--------|----------------|-------|-------|----------------|---------|
| 23.02   | 18.01   | 0.218 | 15.035  | 7.39 ± 0.06   | 5.80 ± 0.03 | 0.13 ± 0.01     | 237 ± 8$^{d}$ | 0.037 ± 0.004$^{d}$ | 16.9 ± 0.1 | Water? |

Notes. Orbital elements – $a$, $q$, $e$, and $i$ – from JPL-Horizons. $H_V$ is the absolute magnitude at $V$ band. $P$ is the rotational period. $\Delta m$ is the peak-to-peak amplitude obtained from the rotational light curve. $D$ and $p_V$ are, respectively, the area-equivalent diameter and the geometric albedo at $V$ band, both obtained from radiometric techniques. Spec. slope is the visible spectral slope. Ices indicates the possible icy species detected from spectra. All uncertainties are 1σ.

References: $^1$Alvarez-Candal et al. (2019), $^2$Lellouch et al. (2017), $^3$Barkume et al. (2008).

& Schaller 2008, see Table 1), and the thermal emission from its surface has been detected with Spitzer/IRAC in July 2007 and later with Herschel/PACS in August 2010. Using the Spitzer and Herschel thermal measurements and $H_V = 7.37 ± 0.09$ mag, Duffard et al. (2014) obtained the area-equivalent diameter ($D_{0.9} = 237 ± 8$ km) and the geometric albedo at $V$ band ($p_V = 0.037 ± 0.004$) of 2002 GZ$_{32}$ via the radiometric technique. Lellouch et al. (2017) updated these radiometric results adding ALMA observations to the Herschel and Spitzer data, obtaining an area-equivalent diameter of $237^{+7}_{-12}$ km and a geometric albedo of $0.036^{+0.006}_{-0.005}$. The large radiometric size derived means that 2002 GZ$_{32}$ is one of the largest objects within the centaur population, similar in size to Chariklo and Chiron. A summary of the orbital elements and most relevant physical characteristics of 2002 GZ$_{32}$ is shown in Table 1, including an updated absolute magnitude ($H_V = 7.39 ± 0.06$ mag) recently obtained by Alvarez-Candal et al. (2019). This new $H_V$ is used for the calculations in this work.

Stellar occultations by only five centaurs – Asbolus, Bienor, Chariklo, Chiron, and Echeclus – have been recorded so far (Ortiz et al. 2020a), and only for three of them (Chariklo, Chiron and, very recently, Bienor; Morales et al., private communication) multichord$^1$ occultations were obtained. A ring system around the centaur Chariklo (Braga-Ribas et al. 2014) and a possible similar structure – still under discussion – around the centaur Chiron (Ortiz et al. 2015; Ruprecht et al. 2015; Sickafus and Sickafus et al. 2020) have been reported from these multichord occultations. This highlights the relevance of observing stellar occultations by the largest centaurs: apart from determining their sizes, shapes, albedos, and other physical properties with high accuracy, detecting new rings might be possible. The discovery of rings around small bodies has opened a new avenue of research within the planetary science. The finding that the TNO dwarf planet Haumea also has a ring (Ortiz et al. 2017) has spurred interest on this topic even more. The possible relationship and physical properties behind the rings around centaurs and TNOs is also a new and exciting way of research that has just started and the astrometric observations performed to predict the stellar occultation, the stellar occultation observations themselves, and the observations to determine the rotational light curve; in Section 3, we detail the reduction and analysis of the stellar occultation data; the limb fit, diameter, 3D shape, albedo, density and search for rings are presented and discussed in Section 4; finally, we present our conclusions in Section 5.

2 OBSERVATIONS

2.1 Predictions

Due to the growing interest in recording stellar occultations by TNOs and centaurs, we have been performing intensive astrometric and photometric campaigns since 2010 in order to predict and to observe these occultations with the aim to obtain relevant physical information (e.g. size, shape, albedo, density, rings) of these bodies (see Ortiz et al. 2020a for a review). In the course of our astrometric campaigns, we found out that the centaur 2002 GZ$_{32}$ would occult a $V = 14.0$ mag star on 2017 May 20. The original prediction of the occultation was obtained around 1 yr prior to the event using our own astrometric observations and the offsets with respect to the orbit JPL#20 as described below. To obtain this prediction, we took 14 images in $2 \times 2$ binning mode of 2002 GZ$_{32}$ on 2016 May 30 and June 14, 23, and 26 with the 4k $\times$ 4k IO:O camera of the Liverpool 2.3-m telescope in Roque de los Muchachos Observatory in La Palma (Spain). The detailed set-up of these observations, including weather conditions and other related information, are shown in Table 2. Bias and sky flat-field frames were taken each night to calibrate the images.

We also took 18 images of the centaur in $2 \times 2$ binning mode on 2017 May 16 with the 4k $\times$ 4k DLR-MKII CCD of the 1.23-m Calar Alto Observatory telescope in Almeria (Spain). More details of this observing run are included in Table 2. Bias frames and twilight sky flat-field frames were taken to calibrate the images. The astrometry obtained from these Calar Alto images allowed us to obtain an independent ‘last minute’ prediction using the offsets with respect to the orbit JPL#23.

The images acquired during the aforementioned observing campaigns were astrometrically solved using Gaia DR1 (Gaia Collaboration 2016a,b Lindegren et al. 2012) that was the most precise astrometric catalogue available at the time of this occultation, Gaia DR2 (Gaia Collaboration 2018) was not yet available. Proper motions of the occulted star were accounted for using the HSOY catalogue (Allmann et al. 2017). The predictions from the two telescopes were obtained using the coordinates of the occulted star (Gaia DR1 4332852996363046368), derived as described above, and the relative astrometry (offsets) of 2002 GZ$_{32}$ with respect to the Jet Propulsion Laboratory orbits JPL#20 (for the 2016 data from the Liverpool Telescope) and JPL#23 (for the 2017 data from Calar Alto). The average 1σ uncertainties in the astrometry obtained from
both telescopes and the offsets with respect to the orbits JPL#20 and JPL#23 are shown in Table 2. These uncertainties translate to 1σ uncertainties of 740 km projected on Earth surface (cross-track) and 10 s in time (along-track) for the Liverpool data and of 840 km projected on Earth surface and 20 s in time for the Calar Alto data. The prediction map obtained from the Liverpool telescope astrometry is shown in the bottom panel of Fig. 1 and the map obtained from the CAHA 1.23-m telescope astrometry is shown in the top panel of the same figure. It is important to note that the two predictions are independent of each other because they are based on independent offsets obtained from the two datasets. Nevertheless, both predictions were compatible within error bars and they have a difference between their central lines of ~100 km in projected distance on Earth surface.

As the original prediction from the Liverpool telescope and the ‘last minute’ one from the Calar Alto telescope were consistent and compatible with each other, we decided to alert our team members and a large list of professional and amateur European collaborators. Six positive detections, at five well-separated sites, and two near misses were finally obtained (see Section 2.2).

### 2.2 Stellar occultation

Series of FITS images or video observations were obtained with 29 telescopes on 2017 May 20, and from six of them (five in Spain and one in Greece) we recorded the disappearance and reappearance of the star. We obtained light curves from those six positive observations at five sites (with two telescopes located at La Hita Observatory) that showed deep drops of different duration around the predicted occultation time. Light curves from the other observing sites were also obtained, putting special care in the negative detections at the two locations closest to the shadow path (Sant Esteve and La Sagra Observatory, both in Spain), because they can notably constrain the projected shape of 2002 GZ32 (see Fig. 2 and Table 3). Apart from these six positive detections (from five sites) and two closest non-detections, the occultation was negative from 21 other telescopes located in Spain (5), UK (2), France (6), Italy (2), Germany (1), Poland (1), Hungary (1), Slovakia (2), and Turkey (1). Two other observatories in Greece, both located under the shadow path, missed the occultation due to bad weather conditions and technical problems, respectively. Table A1 lists all telescopes that participated in the occultation campaign. Robust and reliable clock synchronizations were used in all the observing sites (i.e. Internet Network Time Protocol servers – NTP – or GPS-based Video Time inserters – VTI), the acquisition times of each image were inserted on the corresponding image header. All CCD images were obtained from around 15 min before and after the predicted occultation time. No filters were used in order to maximize the SNR of the photometric data.

The light curves of the occultation (flux versus time) were obtained using our own daophot-based routines (Stetson 1987), coded in the Interactive Data Language (IDL), after the usual bias and sky flat-field calibration of the individual images (i.e. subtracting a
Finally, the combined flux of the occulted star and 2002 GZ 32 chosen aperture radii and comparison stars minimized the flux comparison stars in order to minimize variations due to different telescope and detector set-ups were the same as those chosen for the two in June 2017 (23 and 24) obtaining a total of 128 images. The at Calar Alto Observatory in Almería (Spain) during five nights times, etc.) from where the positive detections were obtained are information about the observatories (telescopes, detectors, exposure

The 2017 May 20 stellar occultation by 2002 GZ32 including the sites (green marks) from the real shadow path (i.e. the reconstructed ellipse fit) of the stellar occultation by 2002 GZ 32 including the sites (green marks) from where the occultation was recorded (Allariz, Javalambre, Aras de los Olmos, and La Hita in Spain, and University of Athens in Greece) and the negative detections (red marks) closest to the shadow path (Sant Esteve and La Sagra in Spain). The green line indicates the centreline of the shadow path and the blue lines the limits of the shadow. Direction of the shadow is shown by the black arrow. Map credit: https://www.gpsvisualizer.com/ and Australian Topography (© Commonwealth of Australia – Geoscience Australia – 2016. Creative Commons Attribution 4.0 International Licence).

median bias and dividing by a median flat-field). Relative aperture photometry of the occulted star (which, around the occultation time, is the combination of the star flux and the 2002 GZ 32 flux) was then obtained on the images using the stars present in the FOV as comparison stars in order to minimize variations due to different seeing conditions and atmospheric transparency fluctuations. The chosen aperture radii and comparison stars minimized the flux dispersion of the occulted star before and after the occultation. Finally, the combined flux of the occulted star and 2002 GZ 32 versus time was obtained for each observing site. From the five locations cited above the obtained light curves show deep drops in flux at the predicted occultation times (see Section 3). Detailed information about the observatories (telescopes, detectors, exposure times, etc.) from where the positive detections were obtained are shown in Table 3, together with the stations closest to the object that reported negative detection.

Note that the observations obtained in video format were converted to FITS images prior to their analysis. The only positive observation acquired in video was the La Hita Observatory T-40cm one, which was used to confirm the positive light curve from the same site using the 77-cm telescope and a CCD detector (see Table 3). Further details on the analysis of the stellar occultation light curves are given in Section 3.

### 3 ANALYSIS OF THE STELLAR OCCULTATION

Table 4 summarizes the occulted star details and other related information. Our occultation data are clearly dominated by the exposure times (≥10.60 km) rather than by the stellar diameter (∼0.59 km at 2002 GZ 32’s distance) or Fresnel diffraction effects (∼0.88 km). To estimate the projected diameter of the occulted star in the plane of the sky we used its B, V, and K apparent magnitudes from the NOMAD catalogue (B = 14.900 mag, V = 14.020 mag, K = 10.290 mag, Zacharias et al. 2004) and the van Belle (1999) equation. The Fresnel scale value of \( F = \sqrt{\lambda d/\lambda} \) results from \( \lambda = 0.88 \) km results from \( \lambda = 0.88 \) km results from

\[
F = \sqrt{\lambda d/\lambda},
\]

\[
V = 14.900 \text{ mag},
\]

\[
K = 10.290 \text{ mag}, \quad \text{and} \quad d = 17.1033 \text{ au}.
\]

The 2017 May 20 stellar occultation by 2002 GZ32 limb. These ‘ingress’ and ‘egress’ times determine different segments in the plane of the sky for each observing site, those segments (expressed in time) can be directly translated to distances using the apparent motion of 2002 GZ 32 relative to the occulted star which is 21.19 km s\(^{-1}\) in our case (see Table 4). The obtained segments in the plane of the sky are called ‘chords’. These chords are used to achieve the results described in Section 4. The ingress and egress times (and associated uncertainties) at each site are obtained by means of the creation of a synthetic light curve using a square-well model convolved with the star apparent size, the Fresnel scale and the exposure time (the star apparent size and the Fresnel effects are negligible in our case, when compared with the exposure times). This synthetic light curve is compared with the data and the difference is iteratively minimized using a \( \chi^2 \) metric, as is described in Ortiz et al. (2017), and in Benedetti-Rossi et al. (2016) and references therein. The times of disappearance and reappearance obtained are shown in Table 5, from these ingress/egress times six chords were obtained with values (in km) also included in Table 5. The uncertainties in the times were small, except for the University of Athens observations due to the long integration time and large deadtimes of the detector. We also note that the video from the La Hita Observatory T-40cm was only used to confirm the positive detection from the same site using the T-77cm and not to perform the limb fit (see Section 4.1), which is hence based on five chords, not six. The reason is two-fold: an estimated 1 per cent of the frames during the video acquisition were lost and the absolute timing was offset by an unknown amount due to a computer problem.

2.3 Rotational light curve

In order to obtain the rotational phase of 2002 GZ 32 at the moment of the occultation, we observed the object with the 1.23-m telescope at Calar Alto Observatory in Almería (Spain) during five nights after the occultation date, three in May 2017 (23, 25, and 26) and two in June 2017 (23 and 24) obtaining a total of 128 images. The telescope and detector set-ups were the same as those chosen for the astrometric campaign (Table 2). The images were acquired in 2 × 2 binning mode with an average seeing during the whole campaign of 1.9 arcsec (2.1 arcsec for the three nights in May and 1.6 arcsec for the two nights in June) and with a Moon illumination ∼4 per cent during the May nights and less than 1 per cent during the June nights.

Flat field and bias standard corrections were applied on the acquired science images. Aperture photometry of the object and of the selected comparison stars was extracted by means of specific routines programed in IDL. Different values for the apertures and sky ring annulus were tried for the object and (same values) for the comparison stars with the aim to minimize the dispersion of the photometry and to maximize the SNR of the object. The data processing was the same as that described in Fernández-Valenzuela et al. (2017). After all this process we obtained the flux of 2002 GZ 32 with respect to the comparison stars versus time – corrected for light travel times. The rotational period of 5.80 ± 0.03 h obtained in Dotto et al. (2008) is used to fold the photometric data, obtaining the rotational light curve shown in Fig. 3. From this rotational light curve, acquired close to the occultation time, we determined that 2002 GZ 32 was near one of its absolute brightness minima (its minimum projected surface) during the event. Based on a fitted Fourier function, its peak-to-peak amplitude is 0.13 ± 0.01 mag, very similar to that of Dotto et al. (2008). The zero rotational phase in the plot was chosen to be at the moment of the stellar occultation (2017 May 20, 01:30:00 UTC).
Table 3. Observation details of the stellar occultation by 2002 GZ32 including positive and negative detections used to constrain the shape of the object. $\sigma_{\text{flux}}$ is the flux dispersion, i.e. the standard deviation of the normalized flux (outside of the occultation in the case of positive detections). All the positive detections used to obtain the limb fit were based on the computer’s system time and the Network Time Protocol (NTP) time synchronized few minutes before the start of the observation.

| Observatory name (City, Country) IAU code | Longitude (E) Latitude (N) Altitude (m) | Telescope characteristics Detector/instrument | Exposure time Cycle time (s) Observer(s) Detection $\sigma_{\text{flux}}$ |
|-------------------------------------------|----------------------------------------|-----------------------------------------------|--------------------------|----------------|----------------|
| Allariz Observatory (Ourense, Spain)      | −07°46′13″0′′ 42°11′57″0′′ 514           | $D = 0.25\,m, f = 1200\,mm$ CCD QHY6            | 1.5                      | L. Pérez       | Positive 0.079 |
| Observatorio Astrofísico de Javalambre (OAJ) (Teruel, Spain) | −01°00′58″6′′ 40°02′30″6′′ 1957 | $D = 0.40\,m, f = 3600\,mm$ ProLine PL4720/e2v CCD47-20-331 | 2.0                      | R. Iglesias    | Positive 0.024 |
| Aras de los Olmos Observatory (Valencia, Spain) | −01°06′05″4′′ 39°56′42″0′′ 1280 | $D = 0.52\,m, f = 3451\,mm$ Finger Lakes Proline 16803 | 0.5                      | V. Peris       | Positive 0.082 |
| La Hita Observatory (Toledo, Spain)       | −03°11′09″8′′ 39°34′07″0′′ 674            | $D = 0.77\,m, f = 2400\,mm$ SBig STX-16803       | 2.0                      | N. Morales     | Positive 0.055 |
| La Hita Observatory (Toledo, Spain)       | −03°11′09″8′′ 39°34′07″0′′ 674            | $D = 0.40\,m, f = 1800\,mm$ Basler AC120         | 0.300                    | L. Ana-Hernandez | Positive 0.096 |
| Univ. of Athens Observatory (Athens, Greece) | 23°47′00″1′′ 37°58′06″8′′ 250             | $D = 0.40\,m, f = 3200\,mm$ SBig ST-10 CCD camera | 0.5                      | K. Gazeas      | Positive 0.101 |
| Sant Esteve Observatory (Barcelona, Spain) | 01°52′21″1′′ 41°29′37″5′′ 180            | $D = 0.40\,m, f = 1600\,mm$ CCD 1/2 in., Mintron 12V1C-EX | 0.16                     | C. Schnabel     | Negative 0.180 |
| La Sagra Observatory (Granada, Spain)      | −02°33′55″0′′ 37°58′56″6′′ 1530           | $D = 0.36\,m, f = 746\,mm$ QHY174M-GPS           | 0.300                    | N. Morales     | Negative 0.089 |

4 RESULTS

Using the chords obtained as described in Section 3, it is possible to derive information about the physical properties of the object itself (Sections 4.1 and 4.2) and analyse the environment around 2002 GZ32 searching for possible rings or debris material orbiting this centaur (Section 4.3).

4.1 Limb fit, diameter, and albedo of 2002 GZ32

From the five chords in bold in Table 5, we have 10 chord extremities that can be used to obtain the projected shape of 2002 GZ32 at the moment of the occultation (i.e. the instantaneous limb). We fitted an ellipse and determined its parameters, as usually done in previous occultation papers (see e.g. Souami et al. 2020), by minimizing the $\chi^2$ function using the simplex method adapted in programs and routines from numerical recipes (Press et al. 1992). In our case, $\chi^2 = \sum_{i=1}^{10} (r_{\text{obs}} - r_{\text{com}})^2 / \sigma_{r_{i}}^2$, where $r$ is the radius from the centre of the ellipse $(f_c, g_c)$, the subscript ‘com’ means computed, the subscript ‘obs’ means observed, and $\sigma_{r_{i}}$ are the uncertainties on the determination of the extremities. It is important to note that the centre of the fitted ellipse $(f_c, g_c)$ provides the offsets in the celestial coordinates (RA, Dec.) to be applied to the adopted ephemeris, JPL J23, assuming that the Gaia DR2 occulted star position is correct. From this fit, we obtained the centre of the ellipse $(f_c, g_c)$, the projected or apparent semi-axes of the ellipse $(a', b')$ and the position angle of the minor axis of the ellipse $(P')$, which is the

Figure 3. Rotational light curve – relative magnitude versus rotational phase – of 2002 GZ32 obtained from data acquired few days after the occultation with the Calar Alto Observatory T1.23-m. The data have been folded with a rotational period of $5.80 \pm 0.03$ h (Dotto et al. 2008). The blue line represents a second-order Fourier function fit. Grey circles at the bottom panel represent the residual of the observational data to the fit. The zero rotational phase in the plot is fixed at the moment of the occultation (2017 May 20, 01:30:00 UTC).
The 2017 May 20 stellar occultation by 2002 GZ$_{32}$  

Table 4. Details of the occulted star and other related information.

| Designation | Gaia DR1 4332852996360346368, UCAC4 385-75921 (Gaia DR2 4332853000658702848) |
|-------------|--------------------------------------------------------------------------------|
| Coordinates DR1$^a$ | $\alpha = 16h 50m 08s.5375, \delta = -13'05''733$ |
| Coordinates DR2$^b$ | $\alpha = 16h 50m 08s.5378, \delta = -13'05''7381$ |
| Magnitudes$^c$ | $B = 14.900, V = 14.020, R = 13.810, J = 11.210, H = 10.444, K = 10.290$ |
| Diameter$^d$ | $\sim 0.0472$ mas ($\sim 0.59$ km at 2002 GZ$_{32}$’s distance) |
| Speed$^e$ | 21.19 km s$^{-1}$ |

Notes.  
$^a$Gaia DR1 coordinates corrected for proper motion using the HSOY catalogue for the occultation date.  
$^b$Gaia DR2 coordinates corrected for proper motion for the occultation date. These coordinates became available after the occultation.  
$^c$From the NOMAD catalogue (Zacharias et al. 2004).  
$^d$Estimated from the $B$, $V$, and $K$ magnitudes using the van Belle (1999) equation.  
$^e$Speed of 2002 GZ$_{32}$ with respect to the star as seen from Earth.

Figure 4. Stellar occultation light curves (normalized flux versus time at mid-exposure) from the five sites where the occultation was recorded. The light curves are ordered from the northern (top) to the southern (bottom) sites: Allariz, Javalambre-OAJ, Aras de los Olmos, La Hita (Spain), University of Athens (Greece). The light curves have been shifted in flux for a better viewing. Error bars are not shown in order to avoid a messy plot. The standard deviation of the measurements are indicated in Table 3.

The Athens chord had a large time uncertainty and led to a bad fit ($\chi^2 = 29.5$), so we decided to slightly shift the chords performing an error bar-weighted linear fit to the centres of the chords (see Fig. 5) under the assumption that the projected body is an ellipse and the centres of its chords must be aligned. Note that an ellipse is a plausible projected shape for 2002 GZ$_{32}$ taking into account that an icy body with its size is expected to be in or near to hydrostatic equilibrium. This time shift approach has been used and justified for other stellar occultations by TNOs and Centaurs, like e.g. was done for the TNO Quaoar in Braga-Ribas et al. (2013) and it is also supported by the errors in time (of the order of several tenths of a second and even larger) reported when using NTP + PC based time for different operating systems and camera control software (e.g. Barry et al. 2015; Ortiz et al. 2020b). The shifts in time obtained from this linear fit are, in all cases, below the chord error bars, as is shown in Table 5 (of course, these shifts in time can be directly translated to shifts in kilometres using the speed of 2002 GZ$_{32}$ with respect to the star as seen from Earth; see Table 4). It is important to note that the ellipse obtained from the unshifted chords fit is fully compatible, within the error bars, with the ellipse obtained from the shifted chords fit. In particular, the semiminor axes obtained from both elliptical fits are the same, and the semimajor axes differ by less than 5 per cent. The limb fit solutions obtained using the original chords and the shifted chords are shown in Table 6. As both solutions are similar and consistent within error bars, we choose the one with the smallest $\chi^2$ as our best solution. The axial ratio of the preferred ellipse is large ($a'/b' = 2.09 \pm 0.24$) which indicates that 2002 GZ$_{32}$ is a very elongated body, as can be seen in Fig. 6 where the 5 (shifted) chords obtained from the occultation are plotted in the plane of the sky with their associated error bars and the best-fitting ellipse to their extremities. The two negative chords closest to the fitted limb (from Sant Esteve and La Sagra in Spain) are also plotted in Fig. 6.

Using the values of the axis instead of the semi-axis of the best-fitting ellipse, we have $(2a, 2b') = (305 \pm 17$ km, $146 \pm 8$ km), from where we can derive the area-equivalent diameter of 2002 GZ$_{32}$ at the moment of the occultation that turns out to be $D_{\text{eqmin}} = 211 \pm 12$ km. This area-equivalent diameter is only a lower limit of the real equivalent diameter of the object because, as was stated in Section 2.3, we know that 2002 GZ$_{32}$ was very close to its absolute brightness minimum at the instant of the occultation, which means that its projected area was also very close to its minimum.

From the best-fitting limb obtained, we derived the geometric albedo at $V$ band of the surface of 2002 GZ$_{32}$ at the moment of the occultation using the expression: $p_V = 10^{(m_V - m_V^\text{sun})/(A/\pi)}$, where $m_V$ is the $V$ magnitude of the Sun ($m_V = -26.74$ mag), $H_V$ is the absolute magnitude of 2002 GZ$_{32}$ at $V$ band ($H_V = 7.39 \pm 0.06$ mag; Alvarez-Candal et al. 2019), and $A$ is the projected area of the centaur that can be directly obtained from the occultation elliptical fit. Finally, to obtain the right albedo, we have to correct $H_V$ taking into account the rotational phase at the instant of the occultation. As we know that the object was close to its minimum projected area during the occultation (Section 2.3), we should add $\Delta m/2 = 0.13/2$ mag = 0.065 mag to $H_V$ to derive the absolute magnitude at the moment of the occultation. A more precise value to be added to $H_V$ during the occultation can be obtained from the Fourier fit to the light
from the elliptical fit (\(p_V\) calculated was used to obtain the instantaneous absolute magnitude, the geometric albedo curve, and it turns out to be of 0.055 mag. After this correction to the first occultation chord, we see that the obtained shifts are below the mean uncertainties of each chord, and the best-fitting ellipse is consistent within error bars.

Under the assumption that the rotational light curve of 2002 GZ\textsubscript{32} is produced by a rotating triaxial ellipsoid with semi-axes \(a\), \(b\), and \(c\) (\(a > b > c\), with \(c\) the axis of rotation) in an equator-on geometry (aspect angle \(= 90^\circ\)), it is possible to relate the amplitude of the light curve \((\Delta m = 0.13 \text{ mag})\) with the axes ratio \(a/b\) using the expression \(\Delta m = 2.5 \log(a/b)\) from which we obtained \(a/b = 1.13\). As the best-fitting ellipse obtained from the occultation is very close to the minimum projected area, it is clear that \(b \approx a'\), and then, the longest semi-axis \((a)\) can be obtained from the amplitude-derived \(a/b\) value \((a = 172.4 \text{ km})\). For the shortest axis \((c)\), it is only possible to provide an upper limit, because the pole position of 2002 GZ\textsubscript{32} is unknown (i.e. the aspect angle is unknown). Then, a possible 3D model for 2002 GZ\textsubscript{32} would have the axes: 2\(a\) = 345 km, 2\(b\) = 305 km, and 2\(c\) = 146 km. From this 3D shape, we can derive a maximum area-equivalent diameter for the centaur (because we only have an upper limit for semi-axis \(c\)) obtaining \(D_{\text{eqmax}} = 225 \pm 12 \text{ km}\). A ‘mean’ area-equivalent diameter of \((D_{\text{eq}}) = 218 \pm 12 \text{ km}\) is obtained from the minimum \((D_{\text{eqmin}}) = 198 \pm 12 \text{ km}\) and maximum (\(D_{\text{eqmax}}) = 225 \pm 12 \text{ km}\) area-equivalent diameter for the centaur (because we only have an upper limit for semi-axis \(c\)).
diameters. This mean diameter is smaller, and not in agreement with the radiometric diameter obtained from thermal data using Herschel and Spitzer (\(D = 237 \pm 8\) km; Duffard et al. 2014), but it is still compatible within error bars with the latest radiometric estimate adding ALMA measurements to Herschel/Spitzer data by Lellouch et al. (2017): \(D = 237^{+12}_{-11}\) km.

The aspect angle, however, does not have to be 90\(^\circ\) (2c \leq 146 km) and, as the occultation took place very close to the minimum of the rotational light curve (minimum projected area), it is possible to search for the aspect angles and triaxial ellipsoids compatible with the projected axial ratio obtained from the occultation (2.09 ± 0.24) and the peak-to-peak rotational light-curve amplitude (0.13 ± 0.01 mag). To do this, we carried out a \(\chi^2\) minimization of the results obtained from a grid search for the aspect angle and the axes (\(2a, 2b, 2c\)) compatible with the aforementioned axial ratio and \(\Delta m\). The aspect angle was explored from 0\(^\circ\) to 90\(^\circ\) at intervals of 0.5 and the axes were explored from (294 km, 294 km, 120 km) to (580 km, 316 km, 146 km) at steps of 4 km. This choice ensures that the space of possible 3D solutions is sampled densely enough and that the minimum \(\chi^2\) solution lies within those intervals. The \(\chi^2\) function to be minimized was defined as \(\chi^2 = (\Delta m - 0.13)^2/0.01^2 + (A_{\mathrm{ratio}} - 2.09)^2/0.24^2 + (b - 152.6)/8.42^2\), with \(\Delta m\) the light-curve amplitude, \(A_{\mathrm{ratio}}\) the projected axial ratio, and \(b\) the semi-axis \(b\) obtained for each triaxial ellipsoid generated during the grid search. From this search, we obtained a family of possible solutions of triaxial ellipsoids and aspect angles. The axes (\(2a, 2b, 2c\)) that meet the constraints ranged from (330 km, 294 km, 120 km) to (402 km, 314 km, 144 km), for aspect angles from 71.5 to 90.0. The triaxial model that minimizes the \(\chi^2\) has axes \(2a = 366\) km, \(2b = 306\) km, \(2c = 120\) km, with an aspect angle of 76\(^\circ\).

We know that 2002 GZ\(_{32}\) produces a double-peaked rotational light curve. The most natural explanation is that the object must be triaxial in shape. If it is a triaxial body in hydrostatic equilibrium, the minimum density that it could have in order to produce a rotational amplitude of 0.13 mag (\(ab/c = 1.13\)) rotating at 5.80 h, would be 1161 kg m\(^{-3}\) using the Chandrasekhar (1987) formalism. If the aspect angle is smaller than 90\(^\circ\), the \(ab/c\) ratio would be larger than 1.13 and the density would be higher too. But the axial ratio \(b/c\) corresponding to a hydrostatic equilibrium body with density 1161 kg m\(^{-3}\) rotating in 5.80 h would be 1.61, whereas the minimum value from the occultation is 2.09. It could be even larger if the object’s aspect angle is smaller than 90\(^\circ\). Hence, the occultation results seem to be incompatible with a hydrostatic equilibrium shape, as is illustrated in Fig. 7.

On the other hand, one must note that 1161 kg m\(^{-3}\) is a large density for an object of 2002 GZ\(_{32}\)’s size, given what we know from several TNOs and centaurs of different sizes, that the density decreases with size (e.g. Grundy et al. 2015; Bieryla & Nimmo 2019). It could be, as it was the case for Haumea (Ortiz et al. 2017), that the real density of the body is considerably lower than the one derived from the hydrostatic equilibrium assumption for a homogeneeous body. In the case of Haumea, the real density is in the 1900–2000 kg m\(^{-3}\) range whereas the hydrostatic equilibrium value was at least 2500 kg m\(^{-3}\). Something similar could be happening with 2002 GZ\(_{32}\). Contrary to Haumea, 2002 GZ\(_{32}\) appears to be too small to be differentiated, so this does not appear to be a plausible explanation.

4.3 Search for rings or debris around 2002 GZ\(_{32}\)

No secondary drops below the 3\(\sigma\) level were detected in the positive occultation light curves (Fig. 4), nor in the ‘best’ (in terms of flux dispersion) of the negative light curves. We can constrain the presence of ring/debris material using those ‘best light curves’ among the positive and negative detections. Within the positive detections, the
Figure 8. Scheme showing a few potential ring geometries around 2002 GZ32, assuming the centaur is rotating around its minor axis and assuming that the rings are equatorial. Rings with different radii and pole orientations are shown, from pole angle of ∼90° (edge-on green ring) to pole angles of ∼84° and ∼72.5° (blue rings) and ∼66.5° (yellow ellipse). The plot illustrates that all ring systems with tilt angles smaller than ∼84° should have given rise to detectable signals in the positive occultation chords (solid red lines) that sampled the main body, provided that the potential rings had sufficiently high optical depth s. Potential rings with tilt angles larger than ∼84° would still be detectable in the light curves that did not detect the primary body (dashed red lines). However, no ring has been detected. Upper limits to the optical depths and widths of the potential rings are shown in Table 7.

from the occultation (Ψ ∼ 71.5–90.0). The best light curve (in terms of flux dispersion) closest to the object’s limb was obtained with the 1.23-m telescope at Calar Alto Observatory, Almeria, Spain (σ_flux = 0.011, see Fig. 9) with exposure times of 0.778 s. The Calar Alto negative detection is at a projected distance on the sky plane of 307 km south from the centre of the limb fit (f_c, g_c), following the ellipse major axis direction (which would correspond to the direction of the major axis of an equatorial ring). In other words, the Calar Alto chord intersects the extended major axis at 307 km distance to the centre of the limb fit (note that this distance is not the distance to the centreline that is shown in Table A1). This distance is close enough to the object to allow the detection of an edge-on ring. As a reference, the two rings around the centaur Chariklo, with a size slightly larger than 2002 GZ32, have orbital radii of 391 and 405 km, respectively (Braga-Ribas et al. 2014). From this light curve, we could have detected a ring around 2002 GZ32 at 3σ if it had a width >0.5 km, for an opacity of 100 per cent. For an opacity of 50 per cent, we could have detected rings with widths >1.1 km at the 3σ level of noise (see Table 7).

The other 22 negative data sets obtained did not provide enough constraints to confirm or rule out the presence of debris at different distances to 2002 GZ32. We have constrained the widths of putative rings for different opacities using all the telescopes larger than 0.8 m outside 2002 GZ32’s limb (see Table 7 and also Fig. 8). It is important to note that the existence of rings at distances larger than the Roche limit (∼500–560 km for an object of 2002 GZ32’s size with ρ = 700–1000 kg m⁻³, respectively) is very unlikely. This means that data from observatories at distances from the shadow-path centreline larger than this limit are not expected to provide constraints on potential rings. We can conclude that no rings or debris material of the kind found around Chariklo have been detected around 2002 GZ32 by means of this stellar occultation, but narrow and thin rings with different geometries cannot be totally discarded.

5 CONCLUSIONS

(i) On 2017 May 20, a multichord stellar occultation of a m_v = 14.0 mag star by the large centaur 2002 GZ32 was detected from
six telescopes in five different observatories located in Spain and Greece. The success of this occultation was possible thanks to a wide international campaign involving 31 telescopes located all over Europe (see Table A1). This is consistent with some of the empirical lessons learnt from ~100 occultations by TNOs/Centaurs detected so far in the sense that a minimum of 15 observatories are typically needed in order to record a multichord occultation (Ortiz et al. 2020a).

(i) A very elongated limb with axis (305 ± 17 km × 146 ± 8 km) was obtained from the best elliptical fit to the occultation data after applying time shifts. From this limb a geometric albedo of \( p_V = 0.043 ± 0.007 \) was derived. This albedo is higher than the radiometric albedos found using Herschel/Spitzer/ALMA thermal data, but compatible with them within error bars. From a rotational light curve obtained using data acquired close to the occultation date, we determined that the occultation took place when 2002 GZ\(_{32}\) was close to its minimum projected area, then the projected area obtained from the occultation directly provides the minimum area-equivalent diameter for this centaur.

(ii) Using the apparent axial ratio from the occultation (\( a'/b' = 2.09 ± 0.24 \)), together with the rotational light-curve constraints (i.e. the peak-to-peak amplitude, \( Δm = 0.13 ± 0.01 \) mag, and the rotational phase at the moment of the occultation), it is possible to derive a 3D shape for 2002 GZ\(_{32}\), obtaining an ellipsoid with axes, 366 km × 306 km × 120 km, as the best solution in terms of a \( χ^2 \) minimization. It is also possible to constrain the aspect angle between 71.5 and 90.0 (minimum \( χ^2 \) for an angle of 76°). The 3D model obtained is not consistent with a homogeneous body in hydrostatic equilibrium (assuming a Jacobi ellipsoid) for the known rotation period of 2002 GZ\(_{32}\). Possible explanations for this non-hydrostatic equilibrium shape should be explored.

(iii) A mean area-equivalent diameter is derived from the maximum and minimum area-equivalent diameters obtained from the occultation (\( D_{\text{sqmax}} = 225 ± 12 \) km, \( D_{\text{sqmin}} = 211 ± 12 \) km) obtaining the value, \( \langle D_{\text{sq}} \rangle = 218 ± 12 \) km. This diameter is smaller than the equivalent diameter obtained from thermal models using observations acquired with Herschel/Spitzer/ALMA \( D = 237^{+11}_{-11} \) km (Lellouch et al. 2017), but it is still compatible within error bars.

(iv) From the occultation light curves, no dense ring or debris material comparable to the structures seen near Chariklo and Chiron were detected orbiting 2002 GZ\(_{32}\). However, very narrow and/or optically thin rings around this centaur cannot be totally discarded.

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Table 7. Ring constraints obtained from telescopes > 0.8 m located at different sites north or south of the limb. The second and third columns are the ring width (w) and minimum optical depth (τ_min) for a 3σ detection. The fourth and fifth columns are the ring widths detectable at 3σ for opacities of 50 per cent and 100 per cent (completely opaque ring), respectively. Sites from north to south sorted by projected distance on the sky plane to the reconstructed centreline, following the ellipse major axis direction, which would correspond to the direction of the major axis of an equatorial ring (D_{MajorAxis}). Note that these distances are different from those shown in Table A1, which are the minimum distances from the centre of the limb fit to the different chords, i.e. following chord perpendicular direction. Positive distances indicate sites north of the centreline, negative distances indicate sites south of the centreline. The Roche limit is around 500–560 km, for densities 700–1000 kg m^{-3}, respectively. The existence of rings at distances larger than the Roche limit is very unlikely.

| Observatory (Telesc., country) | w (km) | τ_min | w(op = 50 per cent) (km) | w(op = 100 per cent) (km) | D_{MajorAxis} | Comments |
|-------------------------------|--------|-------|--------------------------|---------------------------|---------------|----------|
| Skalnate Pleso (1.30 m, Slovakia) | 84.8 | 0.07 | 10.7 | 5.3 | +949 | >Roche limit |
| Konkoly (1.00 m, Hungary) | 2.1 | 0.60 | 1.9 | 1.0 | +843 | >Roche limit |
| Valle D’Aosta (0.81 m, Italy) | 10.6 | 0.60 | 9.5 | 4.8 | +645 | >Roche limit |
| Baronnies Provençales (0.82 m, France) | 8.5 | 0.20 | 3.1 | 1.5 | +506 | ~Roche limit |
| Puimichel (1.04 m, France) | 5.1 | 0.16 | 1.5 | 0.8 | +468 | ~Roche limit |
| Calar Alto (1.23 m, Spain) | 16.5 | 0.03 | 1.1 | 0.5 | -307 | ~Roche limit |
| Sierra Nevada (1.50 m, Spain) | 42.4 | 0.06 | 4.8 | 2.4 | -333 | ~Roche limit |

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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Gaia Collaboration, 2016a, A&A, 595, A2

APPENDIX: SUMMARY TABLE INCLUDING ALL THE OBSERVATORIES AND OBSERVERS THAT SUPPORTED THE OCCULTATION CAMPAIGN

1 Instituto de Astrofísica de Andalucía, IAA-CSIC, Glorieta de la Astronomía s/n, E-18008 Granada, Spain

2 LESIA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, Univ. Paris Diderot, Sorbonne Paris Cité, France
Table A1. Observatories and observers that supported the stellar occultation by 2002 GZ$_{32}$. Sites ordered from north to south sorted by projected distance on the sky plane to the reconstructed centreline. Positive distances indicate sites north of the centre line, negative distances indicate sites south of the centre line.

| Observatory (country)                      | Longitude (E) | Latitude (N) | Telescope aperture | Observer(s)          | Observation | Distance to centreline (km) |
|-------------------------------------------|---------------|--------------|--------------------|----------------------|-------------|----------------------------|
| Borowiec Observatory (Poland)             | 17°04'28.6"   | 52°16'37.2" | 0.40 m             | J. Horbowicz, A. Marciniak | Negative    | +730.9                     |
|                                           | 123           |              |                    |                      |             |                            |
| Smithy Observatory (UK)                   | -00°04'38.2"  | 51°30'23.8" | 0.30 m             | T. Haymes            | Negative    | +656.7                     |
|                                           | 75            |              |                    |                      |             |                            |
| Hamsey Green Observatory (UK)             | -00°04'01.4"  | 51°19'09.4" | 0.28 m             | M. Jennings          | Negative    | +651.5                     |
|                                           | 170           |              |                    |                      |             |                            |
| PDlink Observatory (Slovakia)             | 18°42'09.5"   | 49°24'15.2" | 0.40 m             | P. Delincak          | Negative    | +595.7                     |
|                                           | 680           |              |                    |                      |             |                            |
| Skalnate Pleso Observatory (Slovakia)     | 20°14'02.1"   | 49°11'21.8" | 1.30 m             | T. Pribulla, R. Komžík | Negative    | +584.4                     |
|                                           | 1826          |              |                    |                      |             |                            |
| Neutraubling Observatory (Germany)        | 12°12'57.3"   | 48°59'23.1" | 0.28 m             | B. Kattentidt        | Negative    | +574.1                     |
|                                           | 333           |              |                    |                      |             |                            |
| Konkoly Observatory (Hungary)             | 19°53'41.7"   | 47°55'06.0" | 1.00 m             | A. Pal, Cs. Kiss     | Negative    | +519.3                     |
|                                           | 944           |              |                    |                      |             |                            |
| Landehen Observatory (France)             | -02°32'16.0"  | 48°26'02.1" | 0.25 m             | C. Ratauda           | Negative    | +496.1                     |
|                                           | 87            |              |                    |                      |             |                            |
| Valle D’Aosta Observatory (Italy)         | 07°28'42.0"   | 45°47'22.0" | 0.81 m             | A. Carbognani        | Negative    | +396.8                     |
|                                           | 1675          |              |                    |                      |             |                            |
| Baronnies Provençales Observatory (France)| 05°30'54.6"   | 44°24'29.3" | 0.82 m             | M. Bretton           | Negative    | +311.4                     |
|                                           | 820           |              |                    |                      |             |                            |
| Monte Agliale Observatory (Italy)         | 10°30'53.8"   | 43°59'43.1" | 0.50 m             | F. Ciabattari        | Negative    | +300.3                     |
|                                           | 758           |              |                    |                      |             |                            |
| Puimichel Observatory (France)            | 06°01'15.6"   | 43°58'48.7" | 1.04 m             | J. Lecacheux, S. Moindrot | Negative    | +288.0                     |
|                                           | 725           |              |                    |                      |             |                            |
| Télescope Léonard de Vinci (France)        | 07°04'18.4"   | 43°36'15.7" | 0.40 m             | F. Signoret, A. Fuambu | Negative    | +268.6                     |
|                                           | 130           |              |                    |                      |             |                            |
| Latrape Observatory (France)              | 01°17'24.7"   | 43°14'38.7" | 0.35 m             | J. Sanchez           | Negative    | +224.6                     |
|                                           | 363           |              |                    |                      |             |                            |
| Latrape Observatory (France)              | 01°17'24.4"   | 43°14'38.4" | 0.30 m             | M. Boutet            | Negative    | +224.6                     |
|                                           | 355           |              |                    |                      |             |                            |
| Sabadell Observatory (Spain)              | 02°05'24.6"   | 41°33'00.2" | 0.50 m             | C. Perello, A. Selva | Negative    | +123.9                     |
|                                           | 224           |              |                    |                      |             |                            |
| Forcarei Observatory (Spain)              | -08°22'15.2"  | 42°36'38.3" | 0.50 m             | H. González, R. Iglesias-Marzoa | Negative    | +123.6                     |
|                                           | 670           |              |                    |                      |             |                            |
| Observatory (country) | Longitude (E) | Telescope aperture | Observer(s) | Observation | Distance to centreline (km) |
|-----------------------|--------------|-------------------|-------------|-------------|---------------------------|
| Sant Esteve Observatory (Spain) | 01° 52' 21.1'' | 0.40 m | C. Schnabel | Negative | +119.3 |
| Allariz Observatory (Spain) | -07° 46' 13.0'' | 0.25 m | L. Pérez | Positive | +102.5 |
| Observatorio Astrofísico de Javalambre (OAJ) (Spain) | -01° 00' 58.6'' | 0.40 m | R. Iglesias-Marzoa | Positive | +11.8 |
| Aras de los Olmos Observatory (Spain) | -01° 06' 05.4'' | 0.52 m | V. Peris | Positive | +4.4 |
| Nunki Observatory (Greece) | 23° 30' 28.6'' | 0.40 m | N. Paschalis | Bad Weather | -6.4 |
| La Hita Observatory (Spain) | -03° 11' 09.8'' | 0.77 m | N. Morales | Positive | -34.1 |
| La Sagra Observatory (Spain) | -02° 33' 55.0'' | 0.36 m | N. Morales | Negative | -136.7 |
| La Murta Observatory (Spain) | -01° 12' 10.0'' | 0.40 m | J.A. de los Reyes | Negative | -138.7 |
| Adiyaman University Observatory (Turkey) | 38° 13' 31.5'' | 0.60 m | E. Sonbas | Negative | -182.0 |
| Calar Alto Observatory (Spain) | -02° 32' 54.1'' | 1.23 m | S. Mottola | Negative | -188.8 |
| Sierra Nevada Observatory (Spain) | -03° 23' 05.0'' | 1.50 m | P. Santos-Sanz | Negative | -205.1 |
