2008 OG\textsubscript{19}: a highly elongated Trans-Neptunian object

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ABSTRACT
From two observing runs during the 2014 summer at the Calar Alto Observatory in Almería (Spain) and at the Sierra Nevada Observatory in Granada (Spain), we were able to derive CCD photometry of the Trans-Neptunian object 2008 OG\textsubscript{19}. We analysed the time series and obtained a double-peaked light curve with a peak-to-valley amplitude of 0.437 ± 0.011 mag and a rotational period of 8.727 ± 0.003 h. This implies that this object is very elongated, closely resembling the case of Varuna. The photometry also allowed us to obtain an absolute magnitude in the \(R\) band of 4.39 ± 0.07 mag. From this result, we estimated an equivalent diameter of 2008 OG\textsubscript{19} of 619\textsuperscript{+36}\textsubscript{−31}\textperthousand\imensional km using an average albedo for scattered disc objects. Finally, we interpreted the results under the assumption of hydrostatic equilibrium and found a lower limit for the density of 544\textsuperscript{+42}\textsubscript{−41}\textperthousand\imensional kg m\textsuperscript{−3}. However, a more likely density is 609 ± 4 kg m\textsuperscript{−3} using an aspect angle of 60°, which corresponds to the most likely configuration for the spin axis with respect to the observer assuming random orientations.

Key words: techniques: photometric – Kuiper belt objects: individual: 2008 OG19.

1 INTRODUCTION
Trans-Neptunian objects (TNOs) are bodies that orbit the Sun beyond the orbit of Neptune (e.g. Jewitt, Morbidelli & Rauer 2008). The first TNO to be discovered was 1992 QB\textsubscript{1} by Jewitt & Luu (1993). Although it has been more than 20 years since this population was discovered, our overall knowledge about the physical properties of the objects that reside in the Trans-Neptunian region is still scarce, mainly because of the faintness of these bodies. TNOs are thought to be mainly composed of mixtures of rocks and ice, a similar composition to that of comets (e.g. Elkins-Tanton 2010; Barucci et al. 2011).

Because of their large distance to the Sun, TNOs are thought to be the least evolved in the Solar system. Hence, they yield important information on the composition materials and physical conditions of the primitive solar nebula. The study of these bodies reveals plenty of information on the evolution of the Solar system since its initial phases. Additionally, the Trans-Neptunian belt provides a natural connection with the study of protoplanetary discs observed around other stars.

Because of all the above, we have been carrying out a rotational light-curve survey of TNOs and Centaurs, for nearly two decades (e.g. Lellouch et al. 2002; Ortiz et al. 2002, 2004, 2006, 2007, 2011; Belskaya et al. 2006; Duffard et al. 2008; Santos-Sanz et al. 2008, 2015; Thirouin et al. 2010) in order to gather important physical information about them. In the course of our survey, the TNO with provisional designation 2008 OG\textsubscript{19} has shown interesting features, such as a large amplitude of variability, which encouraged us to make a very detailed study.

2008 OG\textsubscript{19} was discovered in 2008 July from the Palomar Observatory. As far as we know, the only published information on this body comes from a work by Sheppard (2010) in which data about several TNOs are reported. He obtained the absolute magnitude, \(m_{\text{B}}(1, 1, 0) = 4.47 ± 0.02\) mag, and the colours for this object (see table 2 of Sheppard 2010) based on the average of the photometry and assuming a phase slope parameter. However, no further physical information on 2008 OG\textsubscript{19} was presented.

Here we present the first determination of the rotation period and the light-curve amplitude for 2008 OG\textsubscript{19}. The amplitude of the rotational light curve turned out to be remarkably high, which is a clear indication of a very elongated shape for this body. Such elongated bodies are unusual within the Trans-Neptunian belt, with Varuna being the archetype. In Section 2, we describe the technical characteristics of the telescopes used for the observing runs. In Sections 3 and 4, we describe the data reduction and the data analysis, respectively. The results from the light-curve study are also included in Section 4. Furthermore, in Section 5, we report the method to obtain the absolute magnitude and we estimate the equivalent diameter of the target. We discuss all the results in Section 6. Finally, we present our conclusions in Section 7.

2 OBSERVATIONS
We took images of the TNO 2008 OG\textsubscript{19} in two observing runs during 2014 with different telescopes: the 1.23-m Calar Alto Observatory telescope in Almería (Spain) and the 1.5-m Sierra Nevada Observatory telescope in Granada (Spain).

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The first observing run was on July 23, 29, 30 and 31 with the 4k × 4k DLR-MKIII CCD camera of the 1.23-m Calar Alto Observatory telescope. The image scale and the field of view (FOV) of the instrument are 0.32 arcsec pixel$^{-1}$ and 21.5 × 21.5 arcmin$^2$, respectively. The images were obtained in 2 × 2 binning mode and were taken in the R-Johnson filter; the average seeing was 1.41 arcsec (see Table 1). We experienced good weather and dark nights (moonshine maximum ∼14 per cent). The signal-to-noise ratio (S/N) on the first night was ∼26 with 400-s exposure time, whereas the S/N for the remaining nights was ∼40 with 300-s exposure time. The images of 2008 OG$_{19}$ were dithered over the detector to prevent problems in the photometry associated with bad pixels or CCD defects. Bias frames and twilight sky-flat-field frames were taken each night to calibrate the images, and a total of 158 science images were obtained. We aimed the telescope at the same region of the sky each night to have the same stellar field throughout the observing run; this is important so we can choose the same set of comparison stars for all nights in the observing run in order to minimize systematic photometric errors. This is possible because of the large enough FOV of the two telescopes that we have used.

The second observing run was on August 21, 22, 24 and 25 with the 2k × 2k CCD of the 1.5-m Sierra Nevada Observatory telescope. The image scale and the FOV of the instrument are 0.232 arcsec pixel$^{-1}$ and 7.92 × 7.92 arcmin$^2$, respectively. The images were obtained in 2 × 2 binning mode and were taken with no filter to obtain the best S/N (which was ∼40 during the run); the exposure time was 400 s throughout the observing run. We had clear and dark nights; the moonshine was 17 per cent for the first night and 11 per cent for the second night, while the other two nights were completely dark nights. For this run, the average seeing was 1.48 arcsec, slightly worse than the first run. As in the July run from the Calar Alto Observatory, we aimed the telescope again at the same coordinates on all nights. Bias frames and twilight flat-field frames were taken each night to calibrate the exposures. In this run, we took a total of 142 science images. In total, we analysed 300 frames of 2008 OG$_{19}$.

All images were corrected for light travel time. Table 1 presents a selection of the relevant observational data and the orbital data of 2008 OG$_{19}$.

### 3 DATA REDUCTION

To calibrate the images with bias frames and twilight sky-flat-field frames, we subtracted a median bias and divided by a median flat-field corresponding to each night. Specific routines written in IDL (Interactive Data Language) were developed for this task. The routines also included the code to perform the aperture photometry of all comparison stars and 2008 OG$_{19}$. We chose 22 stars for each run with good photometric behaviour. The aperture size was chosen in order to maximize the S/N on the TNO for each night and to minimize the dispersion of the photometry. We tried different apertures until the least dispersion in the residual to the fit to the experimental points in the photometry was obtained (see Section 4). This aperture corresponds to a radius between 4–6 pixels (2.56–3.84 arcsec) and 6–8 pixels (2.78–3.71 arcsec) for the Sierra Nevada Observatory and the Calar Alto Observatory, respectively (see Table 1). The median sky level was determined within an exterior annulus respect to the ring for the photometry with its inner radius equal to the size of the aperture plus 5 pixels, and a width of 5 pixels (in both telescopes). All images were checked in order to confirm the target was not close to any star (in which case, the annulus used to subtract the sky background might be contaminated with light from other stars and the photometry might not be correct). At the time of observation, the angular speed of 2008 OG$_{19}$ was 2.87 arcsec h$^{-1}$. The image trailing due to the motion of the object was only 0.23 and 0.31 arcsec during a typical 300-s and 400-s integration, respectively. This image trailing is negligible when we compare with our nominal 1.44 arcsec full width at half-maximum (FWHM) image quality. Through the aperture photometry, we obtained the flux of all objects versus time (Julian Date). We obtained the relative photometry of the target with respect to each comparison star, so we had 22 light curves in total. To analyse these, we calculated an average of all light curves and plotted this. The results are given in Table 2.

### Table 1. Journal of observations for 2008 OG$_{19}$. The observations on July 23, 29, 30 and 31 belong to the Calar Alto Observatory run. The observations on August 21, 22, 24 and 25 belong to the Sierra Nevada Observatory run. Filters are based on the Johnson–Kron–Cousins system. Seeing is calculated as the average for each night. Quantities are Universal Time date of the observation (UT date), corresponding Julian Date for the first image of the night (JD), aperture radii for photometry (Aper), exposure time ($t_e$), heliocentric distance ($R$), geocentric distance ($\Delta$), phase angle ($\alpha$), light travel time ($t_L$), number of images (N) and time on target each night ($t_{on-target}$).

<table>
<thead>
<tr>
<th>UT date (2014)</th>
<th>JD</th>
<th>Filters</th>
<th>Aper. (arcsec)</th>
<th>$t_e$ (s)</th>
<th>Seeing (arcsec)</th>
<th>$R$ (au)</th>
<th>$\Delta$ (au)</th>
<th>$\alpha$ (deg)</th>
<th>$t_L$ (min)</th>
<th>N</th>
<th>$t_{on-target}$ (h)</th>
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<tr>
<td>July 23</td>
<td>245 6862.442 92</td>
<td>R</td>
<td>2.56</td>
<td>400</td>
<td>1.23</td>
<td>38.5787</td>
<td>37.5806</td>
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<td>312.5482</td>
<td>30</td>
<td>3.33</td>
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<tr>
<td>July 29</td>
<td>245 6868.460 88</td>
<td>R</td>
<td>2.56</td>
<td>300</td>
<td>1.38</td>
<td>38.5788</td>
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<td>0.220</td>
<td>312.4926</td>
<td>33</td>
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<td>July 30</td>
<td>245 6869.445 75</td>
<td>R</td>
<td>3.84</td>
<td>300</td>
<td>1.61</td>
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<td>R</td>
<td>2.56</td>
<td>300</td>
<td>1.42</td>
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<td>0.216</td>
<td>312.4933</td>
<td>51</td>
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<tr>
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<td>245 6891.354 87</td>
<td>Clear</td>
<td>3.71</td>
<td>400</td>
<td>1.53</td>
<td>38.5793</td>
<td>37.6440</td>
<td>0.574</td>
<td>313.0753</td>
<td>33</td>
<td>3.67</td>
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<tr>
<td>Aug 22</td>
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<td>400</td>
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<td>38.5794</td>
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<td>313.1285</td>
<td>37</td>
<td>4.11</td>
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<tr>
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<tr>
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<td>38.5794</td>
<td>37.6712</td>
<td>0.661</td>
<td>313.3017</td>
<td>44</td>
<td>4.89</td>
</tr>
</tbody>
</table>

### Table 2. Photometry results for the observations from the Calar Alto and Sierra Nevada observatories. We list the Julian Date (JD, corrected for the light time), the relative magnitude (Rel. mag., in mag), the error associated (Err., in mag), the topocentric ($r_h$) and heliocentric ($\Delta$) distances (both distances expressed in au) and the solar phase angle ($\alpha$, in deg). The full table is available online.

<table>
<thead>
<tr>
<th>JD</th>
<th>Rel. mag. (mag)</th>
<th>Err. (mag)</th>
<th>$\Delta$ (au)</th>
<th>$r_h$ (au)</th>
<th>$\alpha$ (deg)</th>
</tr>
</thead>
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<td>0.061</td>
<td>37.582</td>
<td>38.581</td>
<td>0.274</td>
</tr>
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<td>0.274</td>
</tr>
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<td>0.047</td>
<td>37.582</td>
<td>38.581</td>
<td>0.274</td>
</tr>
<tr>
<td>245 6862.430 41</td>
<td>−0.085</td>
<td>0.047</td>
<td>37.582</td>
<td>38.581</td>
<td>0.274</td>
</tr>
<tr>
<td>245 6862.435 17</td>
<td>−0.124</td>
<td>0.045</td>
<td>37.582</td>
<td>38.581</td>
<td>0.274</td>
</tr>
<tr>
<td>245 6862.439 93</td>
<td>−0.127</td>
<td>0.048</td>
<td>37.582</td>
<td>38.581</td>
<td>0.274</td>
</tr>
</tbody>
</table>
4 DATA ANALYSIS AND RESULT

To obtain the rotational period of the target, we applied two different techniques to the time series. The first technique was a period search routine based on the Lomb technique (Lomb 1976) as implemented in Press et al. (1992). This method is a modified version of the Fourier spectral analysis to take into account unevenly sampled data. The Lomb periodogram obtained is plotted in Fig. 1(a). As can be seen, the maximum spectral power peak was obtained for the frequency 5.5 cycles d$^{-1}$ (4.364 ± 0.001 h) with a normalized spectral power of 121.6. The maximum for the spectral power is flanked by aliases due to the 24-h sampling periodicity. The second technique was the phase dispersion minimization (PDM) method. Contrary to the Lomb method, which searches the period that maximizes the normalized spectral power, the PDM method searches for the period that minimizes the so-called $\theta$ parameter (Stellingwerf 1978). Fig. 1(b) shows the PDM $\theta$ parameter as a function of rotational frequency (we used frequency steps of 0.0005 cycles d$^{-1}$ within the interval of 0.1–10 cycles d$^{-1}$). Two identical minima were obtained at 5.5 and 2.75 cycles d$^{-1}$ (4.364 ± 0.001 h and 8.727 ± 0.003 h, respectively). Therefore, we consider the 4.364 h and 8.727 h periods as candidate rotational periods.

First, we folded the photometric data with the shorter candidate photometric period 4.364 h. This period produces a single-peaked light curve (Fig. 2). To calculate the single-peaked light-curve amplitude, we fitted the data points using a Fourier function of second order, where $f_0$ is the rotational phase, as follows

$$a_0 + a_1 \cos 2\pi f_0 + b_1 \sin 2\pi f_0 + a_2 \cos 4\pi f_0 + b_2 \sin 4\pi f_0,$$

in order to find the Fourier coefficients ($a_0$, $a_1$, $a_2$, $b_1$, $b_2$).

An amplitude ($\Delta m$) of 0.406 ± 0.011 mag was obtained for the single-peaked light curve. The folded data using the larger candidate period, $P = 8.727 ± 0.003$ h, show that the light curve of 2008 OG$_{19}$ has two maxima and two minima per rotation period (Fig. 3). The amplitude obtained from the fit to equation (1) has, in this case, a value of 0.437 ± 0.011 mag. The Fourier coefficients for the fit of the double-peaked light curve (which is our preferred light curve; see Section 6) are given in Table 3. To estimate the period uncertainty, we searched for all the periods that gave $\chi^2_{\text{pdf}}$ within $\chi^2_{\text{pdf,min}}$ and $\chi^2_{\text{pdf}} + 1$. The $\chi^2_{\text{pdf}}$ value is derived from the fit to the Fourier function with the photometry data points, which was 2.63 for 8.727 h and 2.37 for 4.364 h.

The folded light curve produced using the 24-h alias periods ($P = 3.69$ h, $P = 5.33$ h) are unconvincing and confirm that they are aliases (Fig. 4). We obtained the values of 3.96 and 6.03 for the $\chi^2_{\text{pdf}}$ test applied to fit to the Fourier function with the data points, for the periods of 3.69 and 5.33 h, respectively. These values of $\chi^2_{\text{pdf}}$ are over the $\chi^2_{\text{pdf,min}} + 1$ value that produced the double-peaked light-curve period.
5 Absolute magnitude and equivalent diameter of 2008 OG$_{19}$

An asteroid’s absolute magnitude ($H$) is the visual magnitude when the asteroid is located at unit heliocentric and geocentric distances and at zero phase angle. The diameter of the asteroid ($D$) can be obtained from the absolute magnitude using

$$D = C \cdot p^{1/2} 10^{-[H(S)/5]},$$

(2)

where $C = 1329$ km is a constant and $p$ and $H$ are the geometric albedo and the absolute magnitude of the object in the same photometric band, respectively (e.g. Russell 1916; Chesley et al. 2002).

Because we did not observe Landolt reference stars in our runs at the Calar Alto and Sierra Nevada observatories, we had to calibrate the stellar fields that 2008 OG$_{19}$ traversed with auxiliary data. We took images of the SA 112-250 Landolt standard star (which has a similar colour to 2008 OG$_{19}$, according to the data by Sheppard 2010) and the stellar field in a photometric night. We could not use either the 1.23-m telescope at the Calar Alto Observatory or the 1.5-m telescope at the Sierra Nevada Observatory because they were not available, so we observed with the IAC80 telescope from the Teide Observatory in the Canary Islands (Spain) on 2014 November 24. The instrument used was a CAMELOT CCD camera with 2048 × 2048 pixels. The image scale and the FOV of the instrument are 0.304 arcsec pixel$^{-1}$ and 10.6 × 10.6 arcmin$^2$, respectively. The exposure time of the SA 112-250 images was 10 s and the exposure time of the images of the same stellar region of the Calar Alto run was 50 s.

We measured the flux of the Landolt standard star and the comparison stars and we obtained the magnitudes of the comparison stars. Finally, with the magnitudes of the comparison stars, we calculated the absolute magnitude of 2008 OG$_{19}$ by means of the following equation:

$$H_{R_{r}} = m_{\text{star}} - 2.5 \log \left( \frac{F_{\text{OG}}}{F_{\text{star}}} \right) - 2.5 \log \left( r_{H}^{\text{H}} \Delta^{2} \right) - \phi(\alpha).$$

(3)

Here, $H_{R}$ is the $R$-band absolute magnitude, $m_{\text{star}}$ is the apparent magnitude of each comparison star, ($F_{\text{OG}}$) is an average of the flux during a rotational period of the target in ADUs, $F_{\text{star}}$ is the flux of each of the 22 comparison stars in ADUs, $n$ is an index that reflects the change of the magnitude with the heliocentric distance (2 for asteroids), $r_{H_{r}}$ is the heliocentric distance in astronomical units (au), $\Delta$ is the geocentric distance in au, $\phi$ is the phase angle function and $\alpha$ is the phase angle in degrees.

We calculated the phase angle correction by $\phi = \beta \alpha$, where $\beta = 0.30 \pm 0.12$ mag deg$^{-1}$ was calculated by means of a linear regression via $m_{\beta}(1, 1, \alpha) = H_{R} + \beta \alpha$ to two experimental points $[m_{\beta}(1, 1, \alpha), \alpha]$. One was given in Sheppard (2010) (4.66, 0.88), where he calculated the apparent magnitude based on the average of the photometry$^2$ and the other experimental point was obtained in this study (4.48, 0.27), which is an average of the photometry. This $\beta$ value is slightly high for a TNO. Taking into account this $\beta$ value, we obtained the absolute magnitude of 2008 OG$_{19}$, which is 4.39 ± 0.07 mag in the $R$ band.

Table 5 lists the orbital parameters of 2008 OG$_{19}$. We found that 2008 OG$_{19}$ is a scattered disc object (SDO) following the DES

\footnote{The rotational phases of the photometric measures from Sheppard (2010) are plotted in Fig. 3. As can be seen, the two experimental points of Sheppard are near the minimum and the maximum on the light curve, and hence the average of the photometry matches with the median level of the photometry.}
classification (its Tisserand parameter is equal to 3.03 greater than 3, and its eccentricity is greater than 0.2; Elliot et al. 2005) and a detached object (DO) following the Gladman, Marsden & Vanlaerhoven (2008) classification (its eccentricity is higher than 0.24).

The mean geometric albedo in the V band (derived from Herschel Space Observatory data) for SDOs and DOs is 6.9 and 17.0 per cent, respectively (Santos-Sanz et al. 2012, but note that the sample for DOs is small). We can estimate the geometric albedo in the R band through

\[
\log \left( \frac{p_V}{p_R} \right) = \frac{2}{5} [(V - R)_{\odot} - (V - R)_{\text{OG}}],
\]

where \(p_V\) is the geometric albedo in the V band, \(p_R\) is the geometric albedo in the R band, \((V - R)_{\odot} = 0.36\) mag is the Sun’s \((V - R)_{\text{OG}} = 0.53\) mag is the \((V - R)\) of 2008 OG\(_{19}\) from Sheppard (2010). Therefore, the geometric albedo in the R band is 8.1 and 19.9 per cent for SDOs and DOs, respectively.

Hence, estimates of the equivalent diameter of 2008 OG\(_{19}\) are approximately 868\(_{\pm 36}\) km and 394\(_{\pm 57}\) km, assuming albedos of 8.1 and 19.9 per cent, respectively, which are typical of SDOs and DOs. The equivalent diameter of Varuna is 668\(_{\pm 16}\) km (Lellouch et al. 2013), which is slightly bigger than the equivalent diameter obtained for 2008 OG\(_{19}\) with a typical albedo of SDOs (the group in which Varuna is classified).

6 INTERPRETATION

For minor bodies in the Solar system, a light curve is generally due to albedo variations on the surface, a non-spherical body shape, or a combination of both. In our particular case, we have two options: a single-peaked light curve and a double-peaked light curve. In the first case, this means that it would be due to an albedo variation on the surface. In the second case, this means that it would be due to a triaxial ellipsoid body shape. Therefore, whether the light curve is single-peaked or double-peaked has definite physical implications. In the following subsections, we provide several arguments that point to the double-peaked interpretation being consistent with known physical models.

6.1 Oblate spheroid model

TNOs suffer strong impacts that can convert them into a ‘rubble pile’ (Farinella et al. 1981). After the impact, the rubble pile will adopt a shape determined by the angular momentum and the density. Thus, this kind of object can be treated as a fluid as a first approximation. A fluid object with null angular momentum (\(L = 0\)) is totally spherical. As \(L\) increases, the fluid deforms into an oblate spheroid, a Maclaurin spheroid (Chandrasekhar 1987). In our particular case, if the rotational period of 2008 OG\(_{19}\) is 4.364 h (the light curve is single-peaked with an amplitude of 0.405 mag), we obtain a lower limit for the density of 1699 kg m\(^{-3}\). This density is unusually large for a typical TNO with the estimated equivalent diameter of 619 km, if we assume that it belongs to SDOs (Ortiz et al. 2012).

Including some internal cohesion, not just fluid-like behaviour, we estimated the critical rotation period using the Davidsson (2001) formalism. For a typical density of TNOs (\(\approx 1000\) kg m\(^{-3}\), like Varuna’s density; Jewitt & Sheppard 2002) and assuming an internal cohesion of 0.88\(\rho\) (Davidsson 1999), we obtained a critical rotation period of 4.837 h, slower than the rotation period that produces a single-peaked light curve. Hence, 2008 OG\(_{19}\) would have broken up.

This leads us to think that it is very unlikely that 2008 OG\(_{19}\) has an oblate shape and a rotation period of 4.364 h. Besides, rotational light curves caused by albedo features and capable of producing a very large light-curve amplitude of 0.405 mag are not known in the Kuiper belt (e.g. Gutiérrez et al. 2001; Jewitt & Sheppard 2002; Ortiz et al. 2003; Duffard et al. 2009). Therefore, the natural interpretation of the rotational light curve of 2008 OG\(_{19}\) is that it results from the cyclic variations of the cross-section of a triaxial ellipsoid as seen from an observer on Earth.

6.2 Triaxial ellipsoid model

We considered that the rotational period of 2008 OG\(_{19}\) is 8.727 h. Hence, the body produces a double-peaked light curve due to a prolate ellipsoid body shape, with an amplitude of 0.437 mag. As we stated above, a fluid object with null angular momentum is totally spherical and, as \(L\) increases, the fluid deforms into an oblate spheroid. This happens until a critical value \(L\) = 0.304 from which the body becomes a triaxial Jacobi ellipsoid with semimajor/minor axis \(a/b/c\) where \(a > b > c\) (Chandrasekhar 1987). The axial ratio can be obtained from the known equation

\[
\Delta m = 2.5 \log \frac{a}{b},
\]

where \(\Delta m\) is the double-peaked light-curve amplitude. We obtained an axial ratio \(a/b \approx 1.495\). Hence, we estimated a density \(\rho \geq 544\) kg m\(^{-3}\) and an angular momentum \(L = 0.324\) (from table IV of Chandrasekhar 1987), higher than 0.304. This result is valid if we think that the aspect angle of 2008 OG\(_{19}\) (i.e. the angle between the rotation axis and the line of sight) is 90\(^{\circ}\). Nevertheless, in a random distribution of spin vectors, the probability of observing an object with an aspect angle in the range \(\delta, (\delta + d\delta)\) is proportional to \(\sin(\delta)d\delta\). The average aspect angle \(\delta\) is thus 60\(^{\circ}\) (Sheppard 2004). Therefore, if one supposes that the most probable aspect angle for TNOs is 60\(^{\circ}\), then the light-curve amplitude of a triaxial body with an arbitrary aspect angle is given by

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

where \(\delta\) is the aspect angle (as can be seen, for \(\delta = 90^{\circ}\) it leads to equation 5). Using an aspect angle of 60\(^{\circ}\), we obtained an axial ratio \(b/a\) of 0.513, which implies an axial ratio \(c/a = 0.390\) and a density of 609 kg m\(^{-3}\).

However, as can be seen in Fig. 3, the maxima and minima of the light curves have different depths, which is another indication that the light curve is indeed due to the body shape, because real bodies with perfect symmetry are very unlikely.

Thus, 609 kg m\(^{-3}\) is the more likely density of 2008 OG\(_{19}\) and it is a reasonable value according to the density versus size plot in the supplementary material of Ortiz et al. (2012).

Taking into account the light curve and the light-curve amplitude, Varuna is a similar object to 2008 OG\(_{19}\). However, in terms of the derived density, 2008 OG\(_{19}\) has a smaller density than Varuna. If we assume that the albedo of 2008 OG\(_{19}\) is similar to that of Varuna, then 2008 OG\(_{19}\) would be smaller than Varuna and the smaller density of 2008 OG\(_{19}\) would make sense in this context, because it is already known that small TNOs are less dense than larger TNOs (see fig. S7 in the supplementary material of Ortiz et al. 2012). The most likely explanation for this is a larger porosity in smaller objects, whereas for large TNOs one can expect that the material is more compacted.
2.95 mag is a binary object and usually the eclipses produce minima. Hicks, Simonelli & Buratti (2005) and Varuna. Quantities are light-curve amplitude ($\Delta m$), albedo in the V band ($p_V$), ($V-R$) colour, absolute magnitude in the R band ($H_R$), period ($P$), equivalent diameter ($D$), density ($\rho$) and phase slope parameter ($\beta$).

<table>
<thead>
<tr>
<th>TNO</th>
<th>$\Delta m$ (mag)</th>
<th>$p_V$ (per cent)</th>
<th>V − R (mag)</th>
<th>$H_R$ (mag)</th>
<th>P (h)</th>
<th>D (km)</th>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$\beta$ (mag deg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 OG$_{19}$</td>
<td>0.43$^a$</td>
<td>6.9 (SDOs)/17.0 (DOs)$^d$</td>
<td>0.53$^e$</td>
<td>4.39$^a$</td>
<td>8.727$^a$</td>
<td>619 (SDOs)/394 (DOs)$^a$</td>
<td>609$^a$</td>
<td>0.30$^a$</td>
</tr>
<tr>
<td>Varuna</td>
<td>0.44$^b$</td>
<td>12.7$^f$</td>
<td>0.64$^f$</td>
<td>2.95$^b$</td>
<td>6.34358$^b$</td>
<td>668$^b$</td>
<td>1000$^b$</td>
<td>0.10$^b$</td>
</tr>
<tr>
<td></td>
<td>0.42$^g$</td>
<td></td>
<td>3.192$^d$</td>
<td></td>
<td></td>
<td></td>
<td>0.156$^d$</td>
<td></td>
</tr>
</tbody>
</table>

Notes. $^a$ This work.
$^b$ Belskaya et al. (2006).
$^c$ Lellouch et al. (2013).
$^d$ Assumed from Santos-Sanz et al. (2012).
$^e$ Sheppard (2010).
$^g$ Hicks, Simonelli & Buratti (2005).
$^h$ Thirouin et al. (2010).

Table 5. Comparison of orbital parameters of 2008 OG$_{19}$, Varuna and Eris. Quantities are eccentricity ($e$), semimajor axis ($a$), perihelion distance ($q$) and inclination ($i$). Data taken from the Minor Planet Center.

<table>
<thead>
<tr>
<th>TNO</th>
<th>$e$</th>
<th>$a$ (au)</th>
<th>$q$ (au)</th>
<th>$i$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 OG$_{19}$</td>
<td>0.417</td>
<td>66.197</td>
<td>38.577</td>
<td>13.165</td>
</tr>
<tr>
<td>Varuna</td>
<td>0.051</td>
<td>43.161</td>
<td>40.972</td>
<td>17.156</td>
</tr>
<tr>
<td>Eris</td>
<td>0.441</td>
<td>67.729</td>
<td>37.825</td>
<td>44.099</td>
</tr>
</tbody>
</table>

Varuna has a larger albedo than the average albedo of SDOs, possibly resulting from the water ice spectroscopically detected on its surface. However, unfortunately, the albedo of 2008 OG$_{19}$ is not known and the spectra of 2008 OG$_{19}$ are also lacking. Any spectral evidence for water ice, as in Varuna, might be consistent with a larger than average geometric albedo. Regarding V − R colour, Varuna and 2008 OG$_{19}$ are similar but no information on the albedo can be derived from this. A comparison table of Varuna versus 2008 OG$_{19}$ in terms of physical properties is shown in Table 4. Regarding orbital parameters, 2008 OG$_{19}$ is more similar to Eris except for the inclination, which is higher for Eris than for 2008 OG$_{19}$ (Table 5).

6.3 Binary body model

We can also consider the possibility that 2008 OG$_{19}$ is a binary object, in which case the light curve could be due to the occultation of one component by the other. Using the same methodology as in Jewitt & Sheppard (2002), we obtained a lower limit for the density of 514 kg m$^{-3}$, very close to the density that we obtained from the triaxial Jacobi ellipsoid model with an aspect angle of 90°, so it is possible that the binary model can account for 2008 OG$_{19}$ (as in the case of Varuna). However, we do not have any evidence that 2008 OG$_{19}$ is a binary object and usually the eclipses produce minima and maxima with less soft curvatures (e.g. Noll 2003).

7 CONCLUSIONS

We think that the light curve of 2008 OG$_{19}$ is caused by the rotation of a body of triaxial Jacobi shape, similar to that of Varuna. Both objects have a double-peaked light curve with different depths for the two minima and two maxima. The peak-to-valley amplitude of 2008 OG$_{19}$ is 0.437 ± 0.011 mag (close to Varuna’s amplitude) with a rotational period of 8.727 ± 0.003 h. We also found that the absolute magnitude of 2008 OG$_{19}$ in the R band is 4.39 ± 0.07 mag, with $\beta$ ≈ 0.30 mag deg$^{-1}$, and that the equivalent diameter of 2008 OG$_{19}$ is 619 km using a typical albedo for SDOs (8.1 per cent) and 394 km using a typical albedo for DOs (19.9 per cent). The preferred density for 2008 OG$_{19}$ is 609 kg m$^{-3}$ assuming hydrostatic equilibrium and a 60° aspect angle.

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