



HAL
open science

Photometric study of Centaur (60558) 2000 EC and trans-neptunian object (55637) 2002 UX at different phase angles

Philippe Rousselot, Jean-Marc C. Petit, F Poulet, A Sergeev

► To cite this version:

Philippe Rousselot, Jean-Marc C. Petit, F Poulet, A Sergeev. Photometric study of Centaur (60558) 2000 EC and trans-neptunian object (55637) 2002 UX at different phase angles. *Icarus*, 2005, 176 (2), pp.478-491. <10.1016/j.icarus.2005.03.001>. <hal-03405870>

HAL Id: hal-03405870

<https://hal.science/hal-03405870v1>

Submitted on 27 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Photometric study of Centaur (60558)
2000 EC₉₈ and Trans-Neptunian Object
(55637) 2002 UX₂₅ at different phase angles*

P. Rousselot¹, J-M. Petit¹,

F. Poulet²,

A. Sergeev³

¹Observatoire de Besançon, France

²Institut d'Astrophysique Spatiale, France

³ICAMER, Ukraine

Submitted to *Icarus*

Number of manuscript pages: 47

Number of figures: 7

Number of tables: 12

*Based on observations obtained at the La Silla observatory of the European Southern Observatory (ESO) in Chile, and at the Pik Terskol observatory of the International Center for Astronomical Medical and Ecological Research (ICAMER) in Russia.

Proposed running head: *Photometric study of 2000 EC₉₈ and 2002 UX₂₅*

Name and address to which editorial correspondence and proofs should be directed:

Philippe Rousselot

Observatoire de Besançon

B.P. 1615

25010 Besançon Cedex

France

E-mail: rousselot@obs-besancon.fr

Fax number: (33) 3 81 66 69 44

Abstract

We present photometric observations of Centaur (60558) 2000 EC₉₈ and trans-neptunian object (55637) 2002 UX₂₅ at different phase angles and with different filters (mainly R but also V and B for some data). Results for 2000 EC₉₈ are: (i) a rotation period of 26.802 ± 0.042 hours if a double-peaked lightcurve is assumed, (ii) a lightcurve amplitude of 0.24 ± 0.06 for the R band, (iii) a phase curve with $H=9.03 \pm 0.01$ and $G=-0.39 \pm 0.08$ (R filter) and $H=9.55 \pm 0.04$ and $G=-0.50 \pm 0.35$ (V filter) or a slope of 0.17 ± 0.02 mag.deg⁻¹ (R filter) and 0.22 ± 0.06 (V filter), (iv) the color indices $B-V=0.76 \pm 0.15$ and $V-R=0.51 \pm 0.09$ (for $\alpha=0.1-0.5^\circ$) and 0.55 ± 0.08 (for $\alpha=1.4-1.5^\circ$). The rotation period is amongst the longest ever measured for Centaurs and TNOs. We also show that our photometry was not contaminated by any cometary activity down to magnitude $\simeq 27/arcsec^2$.

For 2002 UX₂₅ the results are: (i) a rotation period of 14.382 ± 0.001 hours or 16.782 ± 0.003 hours (if a double-peaked lightcurve is assumed) (ii) a lightcurve amplitude of 0.21 ± 0.06 for the R band (and the 16.782 hours period), (iii) a phase curve with $H=3.32 \pm 0.01$ and $G=+0.16 \pm 0.18$ or a slope of 0.13 ± 0.01 mag.deg⁻¹ (R filter), (iv) the color indices $B-V=1.12 \pm 0.26$ and $V-R=0.61 \pm 0.12$. The phase curve reveals also a possible very narrow and bright opposition surge. Because such a narrow surge appears only for one point it needs to be confirmed.

Keywords: Centaurs, trans-neptunian objects, photometry, (60558) 2000 EC₉₈, (55637) 2002 UX₂₅

1 Introduction

Kuiper Belt Objects (KBOs), whose existence was confirmed observationally in 1992 (Jewitt and Luu, 1993), represent important clue for the formation and early evolution of the outer solar system. Nowadays, thanks to an important effort deployed in the search of new objects, a relatively large number of KBOs are officially repertoried (about 940 different objects, when Centaurs are included, as of July 2004). Such a sample has already permitted to develop different dynamical models designed to explain the formation of the Kuiper belt (e.g. Levison and Morbidelli, 2003).

The study of the physical properties of KBOs is more complicated, because of the faintness of these objects. So far such studies have been focused mainly on the color indices, leading to some trends in the different categories of KBOs identified by the dynamicists (e.g. Doressoundiram *et al.*, 2002; Hainaut and Delsanti, 2002). Some spectral studies, in the visible or near-infrared range, have also been conducted. Due to the very poor signal-to-noise ratio of these spectra such studies have produced, so far, limited results (Brown, 2000; Lazzarin *et al.*, 2003; Fornasier *et al.*, 2004).

This paper presents observational results based on a different approach of the physical properties of KBOs. This approach consists in studying how the reflected light varies with the phase angle α (i.e. the angle Sun-KBO-Earth). Such an approach has already been used for many solid planetary surfaces, e.g. the moon, asteroids, Saturn's ring or giant planets satellites. For these planetary bodies the opposition surge is a common phenomenon. This phenomenon is a non-linear increase in the average surface brightness as the phase angle decreases to zero.

Two causes of the opposition effect are usually considered: (1) shadow-hiding and (2) interference-enhancement, often called coherent-backscatter. Some general regolith property-dependent characteristics of each mechanism are understood, and several papers are devoted to discuss the relative contribution of both mechanism (Drossart, 1993; Helfenstein *et al.*, 1997, 1998; Hapke *et al.*, 1998; Nelson *et al.*, 2000; Belskaya and Shevchenko, 2000; Shkuratov and Helfenstein, 2001; Poulet *et al.*, 2002).

For “typical” KBOs, located at about 40 AU from the Sun, the maximum possible value of α is about 1.5° . For Centaurs, expected to have very similar physical properties to KBOs, but located closer the Sun, α can reach up to typically 6° (for a heliocentric distance of 10 AU). Compared to the properties of the opposition surges observed for asteroids, for example, which have typically a Half Width at Half Maximum of a few degrees (Belskaya and Shevchenko, 2000), such phase angle ranges can seem to be too limited to really permit an accurate physical modeling. Nevertheless the properties of the opposition surge appearing in the KBOs are not necessarily similar to the one usually observed for the asteroids. Belskaya *et al.* (2003) has pointed out the possibility of a very narrow (i.e. less than a few tenth of a degree) opposition surge.

The observations presented in this paper have been obtained on one Centaur – (60558) 2000 EC₉₈ – and one KBO – (55637) 2002 UX₂₅ – referred to hereafter as 2000 EC₉₈ and 2002 UX₂₅. 2000 EC₉₈ is a Centaur which was discovered on March 3, 2000 at Kitt Peak observatory by Spacewatch (Marsden, 2000). 2002 UX₂₅ is a Trans-Neptunian object (TNO) classified as a “classical” and discovered on October 30, 2002 by the same telescope

(Descour *et al.*, 2002). Table 1 presents the orbital characteristics of both objects. Because of its large inclination, superior to 4.5° , 2002 UX₂₅ can be classified also as a “hot” classical object. Since it has been possible to identify this object on images obtained well before its discovery (Stoss *et al.*, 2002) its orbital elements are very accurate.

We conducted a photometric study of both objects. The main objective was to derive an observational phase function for these targets. This objective has been partially reached. Interesting results have been obtained but complementary data would be also useful to confirm the trends we have detected. This study also includes a search for cometary activity for 2000 EC₉₈.

In the next section the observational data are described for both targets. Section 3 presents the different aspects of our analysis of these data, and in section 4 the results are discussed and compared with similar works already published.

2 Observations and data reduction

2.1 2000 EC₉₈

This Centaur was observed during three different observing runs at La Silla Observatory (Chile), managed by the European Southern Observatory (ESO). Three different telescopes were used: the New Technology Telescope (NTT, a 3.5-m telescope) in April 2001, the Danish 1.54-m telescope in March 2002 and the 3.6-m telescope in April 2003. Table 2 gives the observing circumstances.

The observations conducted with the NTT had for main objective to

search for a cometary coma. Different Centaurs were observed during this observing run, including 2000 EC₉₈, and both nights were dark and photometric. We used the direct imaging camera Superb-Seeing Imager (SUSI 2), equipped with two 2048×4096 CCDs, and with a field of view of 5.5′×5.5′. Given the very small plate scale of the instrument (0.0805″ pixel⁻¹) and the seeing (varying from about 0.9 to 1.3″) we used the 2×2 binned mode.

In order to avoid any trailing due to the proper motion of the object the exposure time was limited to 205 s, corresponding to a motion of 0.3″. Most of the images were obtained with a Bessel R filter, with some others with B and V filters, allowing an accurate determination of the magnitude of the reference stars.

The images were bias-subtracted using an averaged 2-D bias image. The resulting images were flat-fielded for instrumental sensitivity pattern removal using a combination of dome and sky flats (science frames). Using standard star images, we computed the photometric coefficients (zero points, extinction coefficients and color terms) using the IRAF package. 22 images obtained during the first night and 32 obtained during the second night, all in R filter, were used for the coma search. For the photometry only the 22 images of the first night were used. We have chosen not to use the data obtained during the second night for the photometric processing, mainly because of the lack of bright possible reference star appearing in the field of view (the final stability of the photometric reduction could not be checked properly).

The observations of the second observing run were performed at the Danish 1.54-m telescope. Four half-nights (second part) were allocated to this program. The observations were performed with the Danish Faint Object

Spectrograph and Camera (DFOSC), a focal reducer instrument, equipped with a backside illuminated CCD chip 2048×4096 $15 \mu m$ pixels. As the optics of DFOSC cannot utilise the whole area of the CCD, the readout area was only 2148×2102 pixels, which includes 50 pixel pre- and post-overscan regions in the X-direction and 22 masked pixels in the Y-direction. The CCD scale was $0.39'' \text{ pixel}^{-1}$ and the field of view $13.7' \times 13.7'$. Exposures were taken using Bessel BVR filters with typical sequences like RVRB.

Data processing followed the previous lines, just adding the use of the overscan region, and using twilight sky images only for the flat fielding. Here again we could compute the photometric coefficients.

Observations at the 3.6-m telescope used the ESO Faint Object Spectrograph and Camera (EFOSC2) in imaging mode. This instrument is equipped with a 2048×2048 $15 \mu m$ pixel CCD chip. The scale is $0.157'' \text{ pixel}^{-1}$ ($0.314'' \text{ pixel}^{-1}$ for our observations because we used the 2×2 binning mode) and the field of view $5.4' \times 5.4'$. Exposures were taken using Bessel BVR filters with typical sequences like RVRB and exposure times varying from 150 to 180 s (R and V filters) and 240 s for the B filter. The data processing was similar to the one for DFOSC images.

2.2 2002 UX₂₅

This TNO was observed with a 2-m telescope located at the Pik Terskol observatory, managed by the International Center for Astronomical Medical and Ecological Research (ICAMER, Kiyv, Ukraine and Terskol, Russia). This observatory is located in the russian Caucasus at an altitude of 3120 m and the telescope is a 2-m Ritchey Chretien-Coude telescope. The obser-

vations were performed with a focal reducer instrument equipped with a 512×512 $20 \mu m$ pixel CCD chip. The scale is $1.0'' \text{ pixel}^{-1}$ and the field of view $8.5' \times 8.5'$. Exposures were taken mainly with R filter and also with B and V filters.

The target was observed during two observing runs. A first one in October 2003 – when the TNO was at opposition – and a second one in December (first half part of the nights). Table 3 gives the observing circumstances. Some standard stars were observed during both runs and the fields of the second observing run were observed during the first one, in order to check the absolute consistency of the photometric reduction.

The data processing was similar to the one DFOSC and EFOSC2 images. Since the observing nights in October were not all photometric, the photometric coefficients were computed using the coefficients obtained during the first two nights of the December run. The consistency of these coefficients was checked using the standard stars observed during the nights October 19 and October 22, when the sky was photometric. Because all the reference stars (see below) were observed during these two nights it was possible to compute their absolute magnitude.

3 Analysis

3.1 Search for cometary activity on 2000 EC₉₈

Thanks to the data collected with the NTT we have performed a search for a cometary activity on the Centaur 2000 EC₉₈. We first created some special MIDAS scripts in order to extract all the subimages where 2000 EC₉₈ was

clearly visible, as well as similar subimages for a bright star appearing in the same frames. All the subimages extracted were coadded, allowing an accurate determination of the surface brightness profile, both for the reference star and the Centaur. The brightness profiles were obtained by using a small C code, designed to average the pixel intensities for a given radial distance.

It has been possible to co-add a total of 54 different images for 2000 EC₉₈, obtained on April 26 and 27, 2001, corresponding to a total integration time of 3.075 hours. Fig. ?? presents the radial profile obtained. The profile of a reference star is superimposed and adjusted in maximum intensity, in order to permit a better examination of the Centaur profile.

The examination of Fig. ?? shows that 2000 EC₉₈ does not present any sign of cometary activity down to magnitude $\simeq 27/arcsec^2$.

3.2 Lightcurve

The photometric reduction of these observations was based on a two-step process. The first step consisted in determining the absolute magnitudes of a few bright stars, called “reference stars” appearing in the same frames and with similar color indices as the one of the targets ($V-R \simeq 0.5$). This determination was based on images obtained when the sky was photometric.

The second step consisted in performing relative photometry with the different reference stars observed. This relative photometry was performed by aperture-photometry and using an aperture with a radius equal to about 1.3-1.5 times the FWHM of the PSF. In some cases, for 2000 EC₉₈ we have averaged the magnitudes obtained with two successive images, in order to improve their accuracy. Tables 4 to 9 present all the reduced magnitudes

derived from our observations, with the uncertainty given at a one sigma level.

The data were further corrected to obtain the absolute magnitude for a heliocentric and geocentric distance of 1 AU. A second correction was added to the time of the measure to account for the light-time variations due to the changing geocentric distances. Data obtained on April 10, 2003, and October 15, 2003, were used as a reference for 2000 EC₉₈ ($\Delta = 13.552$ AU) and for 2002 UX₂₅ ($\Delta = 41.553$ AU) respectively. Figs. ?? and ?? graphically present these corrected data, respectively for 2000 EC₉₈ and 2002 UX₂₅.

The lightcurve is derived from these corrected data, modelling the light variations of the objects as a Fourier expansion plus a phase effect (Rousselot *et al.*, 2003; Harris *et al.*, 1989):

$$H(\alpha, t) = \bar{H}(\alpha) + \sum_{l=1}^m \left[A_l \sin \frac{2\Pi l}{P}(t - t_0) + B_l \cos \frac{2\Pi l}{P}(t - t_0) \right] \quad (1)$$

The Fourier expansion gives the *rotational lightcurve* of the object. The phase term $\bar{H}(\alpha)$ is fixed for any data with a similar phase angle. In Rousselot *et al.* (2003), the grouping occurred for each magnitude measured in a given night. Here we have extended the grouping to all observations performed with a phase angle in a small range.

For 2000 EC₉₈, we had 4 different values of the phase angle: 0.145 for March 18 and 19, 2002, 0.485 for March 23 and 24, 2002, 1.42 for April 10, 11 and 12, 2002, and 2.81 for April 26, 2001.

For 2002 UX₂₅, we had 4 different values of the phase angle: 0.02 for October 19, 2003, 0.045 for October 16 and 20, 2003, 0.10 for October 14 and 22, 2003, and 1.22 for December 21, 22, 23 and 24, 2003.

To determine the rotational lightcurve, we used only the R filter data for each object. B and V filter data were not numerous enough to represent any improvement. Using them would have increased the number of degrees of freedom.

As explained in Rousselot *et al.* (2003), we determined all our model parameters at once (period, phase terms $\bar{H}(\alpha)$ and Fourier expansion coefficients) using a χ^2 minimization technic (Press *et al.*, 1992).

3.2.1 2000 EC₉₈

On Fig. ??, one clearly sees a magnitude variation during the observations, with a period substantially larger than our longest continuous observation, i.e. longer than 8 hours. So we searched for a good period in the range 500 to 2000 minutes. This yielded two possible periods: 13.401 ± 0.033 hours or 26.802 ± 0.042 hours.

The long period is the double of the short one, to within the error bars, and shows a double peak, while the short period shows only a single peak. The best fit for the long period is reached for a degree of expansion of 2, and yields a bias-corrected χ^2 of 0.833. For the short period, a degree of expansion of 1 gives a similar value for the bias-corrected χ^2 . According to the hypothesis that the lightcurve is due to the rotation of an elongated body, we will consider only the double peak curve with a period of 26.802 ± 0.042 hours.

Fig. ?? shows the actual data, shifted in time according to this period, and shifted in magnitude to account for the phase effect. The dashed and dashed-dotted lines represent the best fit lightcurve following equation (1). The V filter lightcurve was obtained using the same period and degree of

expansion as for the R filter. The peak-to-peak amplitude of the smoothed lightcurve is 0.24 ± 0.06 in R filter. For the V filter we found 0.36 ± 0.09 , nevertheless this amplitude is less accurate, because of the lack of data for certain part of the lightcurve. Only R and V filter data are shown as the quality of the B filter data did not allow us to fit equation (1).

3.2.2 2002 UX₂₅

From Table 7 and Fig. ??, one can see that the rotational lightcurve has a very small amplitude. This makes the determination of the rotational period quite difficult. This also means that the 2002 UX₂₅ is rather spherical, at least in its current projection on the sky, and that it does not have any important surface feature.

We searched for a good period shorter than a day and found three possible values with similar bias-corrected χ^2 . The periods are 16.782 ± 0.003 hours, with degree of expansion 3, 14.382 ± 0.001 hours, with degree 8 and 7.1908 ± 0.0004 hours, with degree 6. All three periods seem perfectly compatible with the data. Also, all these lightcurves show multiple peaks superimposed on a single (for the shortest period) or double (for the 2 longest periods) non-symmetrical oscillation. The smoothest fit is shown in Fig. ?? for period 16.782 hours. The peak-to-peak amplitude of the smoothed lightcurve is 0.21 ± 0.06 . Given the very small number of data in V and B filters, it was not possible to fit them with equation (1). It is important to note that we do not claim that this is the correct period, but we use it for display purpose only. As it will be seen below, the actual period does not change the phase curve, which is what we are interested in the end. Similarly to 2000 EC₉₈, we tend to favor the

lightcurves with double peak.

Improving the determination of the period would require a set of high signal to noise data points, which can be obtained only with a large aperture telescope, such as a 4-m class telescope with good seeing.

3.3 Phase function

3.3.1 2000 EC₉₈

As described in section 3.2, we modelled the phase curve $\bar{H}(\alpha)$ with a stepwise function with constant value over each group of phase angles. Hence the fitted function depended linearly on the Fourier coefficients and the $p = 4$ (or 3 for the V filter) values of $\bar{H}(\alpha)$. The best fit values of those parameters were all obtained at once. Values of $\bar{H}(\alpha)$ for R and V filters are presented in Fig. ?? for the double peak long period lightcurve of Fig. ??.

The error bars on the parameters are derived analytically from the fit. We checked that they are consistent with those obtain with a Monte Carlo method that generates 1000 fake lightcurves and fit them again (Rousselot *et al.*, 2003). The good agreement between these two methods leads us to believe our initial estimate of the errors on the measured magnitudes is correct.

3.3.2 2002 UX₂₅

Precise determination of the period is made difficult by the small peak-to-peak amplitude of the signal, which in the same time makes the determination of the phase effect less sensitive to the determination of the period. It turns

out that the phase functions derived for each of the three previous periods are compatible with each other. Fig. ?? shows this function for the same 16.782 hours period as in Fig. ?. The most important character of this function is the potentially very narrow opposition effect that can be seen below 0.1° phase angle. This would warrant more observations at low phase angle ($\alpha < 0.1^\circ$) and intermediate phase angle ($0.5^\circ < \alpha < 0.7^\circ$).

4 Discussion

4.1 2000 EC₉₈

From the phase function curves we derived the standard H and G parameters of Bowell's *et al.* (1989) formalism (Table 10). The same data were also used to compute the color index V-R for two different phase angle ranges (Table 11). The V-R color index does not present any significant change with the phase angle inside the uncertainties. If a color effect exist for the phase function curve it is too small to be detected with our data. Since we didn't get the phase curve for the B filter, the B-V color index presented in Table 11 was computed directly from the photometric measurements given in Table 5 and 6 using successive measurements in V and B filters.

The absolute H_R magnitude allows to estimate the diameter of 2000 EC₉₈ using Russell's equation (Russell, 1916):

$$D = 2\sqrt{\frac{2.24 \times 10^{16} \times 10^{0.4(R_s - H_R)}}{p_R}}, \quad (2)$$

where D is the diameter of the object (in km), R_s is the Sun's R magnitude,

H_R is the object’s absolute magnitude in the R band (given in Table 10) and p_R the geometric albedo in the R band. With $R_s = -27.26$ (Allen, 1976) and a red albedo in between 0.04 (the canonical value of cometary nuclei) and 0.10 (the largest one ever measured so far (Altenhoff *et al.*, 2004), Chiron excepted, which is known to have a cometary activity) this leads to a diameter of $\sim 50\text{--}80$ km. Such a diameter classifies 2000 EC₉₈ as a “normal size” Centaur.

Assuming the brightness change is due to an elongated shape, we can compute a lower limit for the axis ratio a/b , where a and b are the semiaxes such as $a \geq b$ (the rotation axis being supposed perpendicular to the line of sight). If Δm_R is the lightcurve amplitude we have:

$$a/b \geq 10^{0.4\Delta m_R} \quad (3)$$

Using $\Delta m_R = 0.24$ we obtain $a/b \geq 1.25 : 1$. This is not the only possible interpretation, and the difference in amplitude between the R and V filters hints towards a lightcurve due to a change in apparent albedo as the object rotates. This possibility is further enhanced by the quasi symmetry between the two parts of the rotational lightcurve in Fig. ???. In such a case, the single-peaked lightcurve would be more realistic and the rotational period would be 13.401 hours.

4.2 2002 UX₂₅

Contrary to the case of 2000 EC₉₈ we could derive the standard H and G parameters for 2002 UX₂₅ only in the R band (Table 10). We computed the

color indices with the few measurements acquired in all 3 filters at roughly the same time. This is not the best way to compute these quantities, but the only available to us in this case. The resulting uncertainties are somewhat larger than for 2000 EC₉₈ (Table 11).

The absolute H_R magnitude of 2002 UX₂₅ is among the brightest known for a KBO. As of July 2004 only about 10 KBOs or Centaurs, out of more than 940 known objects, have such a low (or lower) H_R magnitude. With a red albedo comprised between 0.04 and 0.10 it leads to a diameter equal of ~ 720 – 1140 km (see equation 2 above). 2002 UX₂₅ is, then, among the biggest KBOs known so far.

Here we have only one lightcurve in R filter. And the lightcurve is all but symmetrical. The brightness variation is most probably due to a surface feature. We can nevertheless put an upper limit to the potential elongation of the object. Using $\Delta m_R = 0.21$ we obtain $a/b \geq 1.21 : 1$.

4.3 Comparison with other works

This work provides, for two different objects, four different types of informations: (i) the color indices (and the absolute magnitudes), (ii) the lightcurve amplitude, (iii) the rotation period and (iv) the phase curve. It is interesting to compare these results to the other works already published, especially for the phase curve, for which very few data are available yet.

The color indices presented in Table 11 can be compared to the other ones published for similar objects (e.g. Peixinho *et al.*, 2004). 2002 UX₂₅ corresponds to a typical classical object, but appears among the reddest “hot classical” objects. The Centaurs measured so far fall into two sub-groups.

2000 EC₉₈ belongs to the sub-group with lowest V-R and B-V color indices. Our value of V-R for 2000 EC₉₈ is similar to the one published by Bauer *et al.* (2003) (0.47 ± 0.06).

The lightcurve amplitudes can also be compared to the statistics already available. Both 2000 EC₉₈ and 2002 UX₂₅, with a R lightcurve amplitude of 0.24 and 0.21, appear to have a relatively large but not exceptional lightcurve amplitude, when compared to other similar objects (Ortiz *et al.*, 2003a).

Table 12 presents an overview of all the Centaurs and TNOs for which a rotation period has been published, including our results. 2000 EC₉₈ has one of the longest period ever measured for a Centaur or TNO. There are only two other objects (1997 CV₂₉ and 1999 UG₅) that have possibly a rotation period as long as this Centaur (if a double-peaked lightcurve is assumed and taking into account the longest possible period for the first object). 2002 UX₂₅ presents a more common rotation period, in between the one of Quaoar and Varuna, that have comparable size. Both objects have a rotation period well above the critical 3.3 hours corresponding to a spherical body with a density of 1 g.cm^{-3} (Romanishin and Tegler, 1999).

The phase curves of 2000 EC₉₈ and 2002 UX₂₅ can be compared to the ones already published using either the standard H-G scattering parametrization or the slope of a linear approximation of the brightness decrease. As pointed out by Rousselot *et al.* (2003) neither of these comparison is really significant. The H-G formalism is not really relevant for TNOs and Centaurs because it was established for asteroids which have obviously very different surfaces and a phase function known for a much broader range of phase angle

values. The comparison of linear slopes is also irrelevant because the phase curve is *not* linear. Unfortunately, because these two parameterizations are the only one published so far they are still the easiest ones to use for a general comparison.

Table 10 shows that the G parameter for 2000 EC₉₈ is negative for both R and V bands. The one for 2002 UX₂₅ is either positive or very close to zero. A negative G would be surprising for an asteroid, since this formalism was originally designed to describe all type of surfaces with $0 \leq G \leq 1$ (the negative values are not formally excluded, however). The G=0 value was designed to describe the darkest surfaces of the asteroids and the G=1 value the brightest ones. A small, or negative value would be an indication of a very low albedo surface, as it is already generally assumed for KBOs.

Four different works have been published that present phase function of TNOs and/or Centaurs with the H-G formalism (Bauer *et al.*, 2002; Sheppard and Jewitt, 2002; Bauer *et al.*, 2003; Rousselot *et al.*, 2003) and they give mostly negative G factors. On the 16 different objects for which the G values was explicitly calculated (excluding this work and Pluto) only five have a positive value: the Centaurs Chariklo, Hylonome, Pholus, 1998 SG₃₅ and 2001 BL₄₁ (Bauer *et al.*, 2003). For these objects the G factors published are below the median value for asteroids (0.08 to 0.17).

Note however that the results of the H-G formalism have to be taken with care for such phase curves, because of the very limited phase angle range covered by the observations (and, sometimes, the very limited number of data available; some G parameters published by Sheppard and Jewitt (2002) are based on only two points on the phase curve). The fact that

only Centaurs present, so far, positive G values may be correlated to the larger phase angle range covered. The main conclusion based on the H-G formalism is probably the poor capability of this formalism to describe the phase function for low albedo surfaces, such as the one of Centaurs or TNOs. This issue was already pointed out by other authors (see e.g. Belskaya and Shevchenko, 2000).

The other way to compare our results with other authors is to assume a linear increase of the magnitude m_R with phase angle α such that $m_R = m_0 + \beta\alpha$. Such a formula is a very crude approximation of the phase function. Nevertheless, when the phase angle coverage is very limited, it can provide a quick way to look at the importance of the opposition surge. For 2000 EC₉₈ our phase curve leads to $m_0 = 9.10 \pm 0.03$ and $\beta = 0.17 \pm 0.02$ (R filter) and $m_0 = 9.59 \pm 0.05$ and $\beta = 0.22 \pm 0.06$ (V filter), and for 2002 UX₂₅ similar calculations lead to $m_0 = 3.34 \pm 0.01$ and $\beta = 0.13 \pm 0.01$ (R filter).

Our β values are in good agreement with the one already published. The mean value published by Sheppard and Jewitt (2002), based on 7 different objects, is 0.15 mag.deg⁻¹. The other values published so far (Shaefer and Rabinowitz, 2002; Rousselot *et al.*, 2003; Belskaya *et al.*, 2003) vary from 0.084 to 0.145 mag.deg⁻¹. Our β values do not present a special difference with the other ones already published.

While an artefact on our data cannot be excluded, 2002 UX₂₅ exhibits an unusual narrow photometric opposition effect at phase angles smaller than 0.1 deg (Fig.??). Opposition effect appearing at phase angles less than 0.1-0.2 deg has also been detected for some Centaurs and KBOs (Belskaya *et al.*, 2003). Amongst atmosphereless planetary satellites, only Rhea, Europa,

and Ariel have similar opposition effect (Domingue *et al.*, 1991; 1995). This could be the result of the shadow-hiding effect due to the porosity of the surface (Hapke, 1986; Hillier, 1997) and/or of a second effect called coherent backscattering which depends primarily on the grain size and the albedo of the regolith particles (Muinonen, 1989; Mishchenko and Dlugach, 1992, 1993; Shkuratov *et al.*, 1999; Poulet *et al.*, 2002). Assuming the shadow-hiding as the possible explanation, the surface of 2002 UX₂₅ has to be extremely porous with values of the porosity certainly larger than 95%. If coherent backscattering mainly contributes to the unusual photometric behavior, then the assumed low-albedo particles of regolith have to be very small to allow the effect of multiple scattering to be responsible of the coherent backscattering. Precise modelings would better quantify the respective contribution of these two effects, but complementary observations at very small phase angles, are necessary to give a firm conclusion on this problem. If a very narrow opposition surge is confirmed it would be an exciting discovery for the KBOs.

5 Conclusion

The data presented in this paper provide more photometric informations on one Centaur – 2000 EC₉₈ – and one TNO, 2002 UX₂₅. The main results concern their rotation period which is 26.802 ± 0.042 hours for the Centaur (one of the longest one ever measured for Centaurs and TNOs) and 14.382 ± 0.001 hours or 16.782 ± 0.003 hours for 2002 UX₂₅ (assuming a double peak rotational lightcurve). Note that for 2002 UX₂₅, the period value

could not be firmly established due to the small lightcurve amplitude, and the real period could be different from those quoted here. Our NTT observations also allowed us to search for cometary activity on 2000 EC₉₈ down to magnitude $\simeq 27/\text{arcsec}^2$, with negative results.

The phase curve derived from our data are similar to the one already published for similar objects, except for a possible very narrow opposition surge in 2002 UX₂₅ that needs to be confirmed. For this target complementary observations are welcome, especially at very small phase angles, both to improve the period determination and the phase curve. Given the bright absolute magnitude of 2002 UX₂₅ and, consequently, its probable large diameter (between 720 to 1140 km, depending of its albedo) some direct determination of its albedo and diameter, with radio observations, would probably be possible and certainly very useful. As already mentioned in Rousselot *et al.* (2003), the H and G formalism of Bowell *et al.* (1989) may not be well suited for KBOs.

The other parameters presented in this paper, i.e. the color indices and lightcurve amplitudes of both objects, do not differ significantly to the similar parameters published for other TNO or Centaurs.

Acknowledgements

The authors are grateful to both the National Academy of Science of Ukraine and the Russian Academy of Science, co-funders of ICAMER, for allowing them access to the Pik Terskol observatory.

References

- Allen, C.W., 1976. *Astrophysical quantities*. University of London, The Athlone press. Third Edition (reprinted with corrections)
- Altenhoff, W.J., Bertoldi, F., Menten, K.M., 2004. Size estimates of some optically bright KBOs. *Astron. Astrophys.* 415, 771-775
- Bauer, J.M., Meech, K.R., Fernández, Y.R., Farnham, T.L., Roush, T.L., 2002. Observations of the Centaur 1999 UG₅: evidence for a unique outer Solar System surface. *Publ. Astron. Soc. Pacific* 114, 1309-1321
- Bauer, J.M., Meech, K.R., Fernández, Y.R., Pittichova, J., Hainaut, O.R., Boehnhardt, H., Delsanti, A.C., 2003. Physical survey of 24 Centaurs with visible photometry. *Icarus* 166, 195-211
- Belskaya, I.N., Barucci, A.M., Shkuratov, Y.G., 2003. Opposition effect of Kuiper belt objects: preliminary estimations. *Earth, Moon and Planets*, 92, 201-206
- Belskaya, I.N., Shevchenko V.G., 2000. Opposition effect of asteroids. *Icarus* 147, 94-105
- Bowell, E., Hapke, B., Domingue, D., Lumme, K., Peltoniemi, J., Harris, A. W., 1989. Application of photometric models to asteroids. In *Asteroids II* (R.P. Binzel, T. Gehrels and M.S. Matthews, Eds), Univ. of Arizona Press, Tucson, pp 524-556
- Brown, M.E., 2000. Near-infrared spectroscopy of Centaurs and irregular satellites. *Astron. J.* 119, 977-983
- Buie, M.W., Bus, S.J., 1992. Physical observations of (5145) Pholus. *Icarus* 100, 288-294
- Chorney, N., Kavelaars, J.J., 2004. A rotational light curve for the Kuiper belt object 1997 CV₂₉. *Icarus* 167, 220-224

Davies, J.K., McBride, N., Ellison, S.L., Green, S.F., Ballantyne, D.R., 1998. Visible and infrared photometry of six Centaurs. *Icarus* 134, 213-227

Descour, A.S., Holvorcem, P.R., Swartz, M., Marsden, B.G., 2002. 2002 UX₂₅. MPEC 2002-V08

Domingue, D. L., Hapke, B.W., Lockwood, G.W., Thompson, D.T., 1991. Europa's phase curve: Implications for surface structure. *Icarus* 90, 30-42

Domingue, D. L., Lockwood, G.W., Thompson, D.T., 1995. Surface textural properties of icy satellites: A comparison between Europa and Rhea. *Icarus* 115, 228-249

Doressoundiram, A., Peixinho, N., de Bergh, C., Fornasier, S., Thébault, P., Barucci, M.A., Veillet, C., 2002. The color distribution in the Edgeworth-Kuiper belt. *Astron. J.* 124, 2279-2296

Drossart, P., 1993. Optics on a fractal surface and the photometry of the regoliths. *Planet. Space Sci.*, 41(5), 381-393

Fornasier, S., Dotto, E., Barucci, M.A., Barbieri, C., 2004. Water ice on the surface of the large TNO 2004 DW. *Astron. Astrophys.* 422, L43-L46

Hainaut, O.R., Delahodde, C.E., Boehnhardt, H., Dotto, E., Barucci, M.A., Meech, K.J., Bauer, J.M., West, R.M., Doressoundiram, A., 2000. Physical properties of TNO 1996 TO₆₆; Lightcurves and possible cometary activity. *Astron. Astrophys.* 356, 1076-1088

Hainaut, O.R., Delsanti, A.C., 2002. Colors of minor bodies in the outer solar system. *Astron. Astrophys.* 389, 641-664

Hapke, B., 1986. Bidirectional reflectance spectroscopy. 4. The extinction coefficient and the opposition effect. *Icarus* 67, 264-280

Hapke, B., Nelson, R., Smythe W., 1998. The opposition effect of

the moon: coherent backscatter and shadow hiding. *Icarus* 133, 89-97

Harris, A.W, Young, J.W., Bowell, E., Martin, L.J., Millis, R., Poutanen, M., Scaltriti, F., Zappalà, V., Schober, H.J., Debehogne, H., Zeigler, K.W., 1989. Photoelectric Observations of Asteroids 3, 24, 60, 261 and 863. *Icarus*, 77, 171-186

Helfenstein, P., Veverka, J., Hillier, J., 1997. The lunar opposition effect: a test of alternative models. *Icarus* 128, 2-14

Helfenstein, P., and 21 colleagues. 1998. Galileo observations of Europa's opposition effect. *Icarus* 135, 41-63

Hillier, J. K., 1997. Shadow-hiding opposition surge for a two-layer surface. *Icarus* 128, 15-27

Hoffmann, M., Fink, U., Grundy, W. M., Hicks, M., 1993. Photometric and spectroscopic observations of 5145 Pholus. *J. Geophys. Res.* 98, 7403-7407

Jewitt, D., Luu J., 1993. Discovery of the candidate Kuiper belt object 1992 QB₁. *Nature* 362, 730-732

Jewitt, D.C., Sheppard, S.S., 2002. Physical properties of Trans-Neptunian object (20000) Varuna. *Astron. J.* 123, 2110-2120

Lazzarin, M., Barucci, M.A., Boehnhardt, H., Tozzi, G.P., de Bergh, C., Dotto, E., 2003. ESO large programme on physical studies of trans-neptunian objects and centaurs: visible spectroscopy. *Astron. J.* 125, 1554-1558

Levison, H.F., Morbidelli, A., 2003. The formation of the Kuiper belt by the outward transport of bodies during Neptune's migration. *Nature* 426, 419-421

Marcialis, R.L., Buratti J., 1993. CCD photometry of 2060 Chiron in 1985 and 1991. *Icarus* 104, 234-243

- Marsden, B.G., 2000. Eight TNOs and Centaurs. MPEC 2000-E64
- Mishchenko, M. I., Dlugach, Zh.M., 1992. Can weak localization of photons explain the opposition effect of Saturn's rings ? Mon. Not. R. Astr. Soc. 254, 15P-18P
- Mishchenko, M. I., Dlugach, Zh. M., 1993. Coherent backscatter and the opposition effect for E-type asteroids. Planet. Space Sci. 41, 173-181
- Mueller, B.E.A, Hergenrother, C.W., Samarasinha, N.H., Campins, H., McCarthy Jr, D.W., 2004. Simultaneous visible and near-infrared time resolved observations of the outer solar system object (29981) 1999 TD₁₀. Icarus, In press
- Muinonen, K., 1989. Electromagnetic scattering by two interacting dipoles. In Proceedings 1989 URSI Electromagnetic Theory Symposium, Stockholm, pp. 428-430
- Nelson, R.M., Hapke, B.W., Smythe, W.D., Spilker L.J., 2000. The opposition effect in simulated planetary regoliths. Reflectance and circular polarization ratio change at small phase angle. Icarus 147, 545-558
- Ortiz, J.L., Baumont, S., Gutiérrez, P.J., Roos-Serote, M., 2002. Lightcurves of Centaurs 2000 QC₂₄₃ and 2001 PT₁₃. Astron. Astrophys. 388, 661-666
- Ortiz, J.L., Gutiérrez, P.J., Casanova, V., Sota, A., 2003a. A study of short term rotational variability in TNOs and Centaurs from Sierra Nevada Observatory. Astron. Astrophys. 407, 1149-1155
- Ortiz, J.L., Gutiérrez, P.J., Sota, A., Casanova, V., Teixeira, V.R., 2003b. Rotational brightness variations in Trans-Neptunian object 50000 Quaoar. Astron. Astrophys. 409, L13-L16
- Ortiz, J.L., and 11 colleagues. 2004. A study of Trans-Neptunian object 55636 (2002 TX₃₀₀). Astron. Astrophys. 420, 383-388

- Peixinho, N., Boehnhardt, H., Belskaya, I., Doressoundiram, A., Barucci, M.A., Delsanti, A., 2004. ESO large program on Centaurs and TNOs: visible colors – final results. *Icarus* 170, 153-166
- Poulet, F., Cuzzi, J.N., French, R.G., Dones, L., 2002. A study of Saturn's ring phase curves from HST observations. *Icarus* 158, 224-248
- Press, W.H., Teukolsky, S.A., Vetterling, W.F., Flannery, B.P., 1992. *Numerical recipes in Fortran; the art of scientific computing*, ed. W.H. Press (Second Edition, Cambridge University Press)
- Romanishin, W., Tegler, S.C., 1999. Rotation rates of Kuiper-belt objects from their light curves. *Nature* 398, 129-132
- Romanishin, W., Tegler, S.C., Rettig, T.W., Consolmagno, G., Botthof, B., 2001. 1998 SM₁₆₅: a large Kuiper belt object with an irregular shape. *Proc. Natl. Acad. Sci.* 98, 11863-11866
- Rousselot, P., Petit, J.M., Poulet, F., Lacerda, P., Ortiz, J., 2003. Photometry of the Kuiper-Belt object 1999 TD₁₀ at different phase angles. *Astron. Astrophys.* 407, 1139-1147
- Russell, H.H., 1916. On the albedo of the planets and their satellites. *Astrophys. J.* 43, 173-196
- Schaefer, B.E., Rabinowitz, D.L., 2002. Photometric light curve for the Kuiper belt object 2000 EB₁₇₃ on 78 nights. *Icarus* 160, 52-58
- Sheppard, S.S., Jewitt, D.C., 2002. Time-resolved photometry of Kuiper belt objects: rotations, shapes, and phase functions. *Astron. J.* 124, 1757-1775
- Sekiguchi, T., Boehnhardt, H., Hainaut, O.R., Delahodde, C.E., 2002. Bicolour lightcurve of TNO 1996 TO₆₆ with the ESO-VLT. *Astron. Astrophys.* 385, 281-288
- Shkuratov, Y.G., Helfenstein, P., 2001. The opposition effect and the quasi-fractal structure of regolith: I. Theory. *Icarus*, 152, 96-116

Shkuratov, Y. G., Kreslavsky, M.A., Ovcharenko, A.A., Stankevich, D.G, Zubko, E.S., 1999. Opposition effect from Clementine data and mechanisms of backscatter. *Icarus* 141, 132-155

Stoss, R., and 14 colleagues, 2002. 2002 UX₂₅. MPEC-V22

William, I.P., O'Ceallaigh, D.P., Fitzsimmons, A., Marsden, B.G., 1995. The slow-moving objects 1993 SB and 1993 SC. *Icarus* 116, 180-185

Table 1: Orbital characteristics of 2000 EC₉₈ and 2002 UX₂₅.

Object	a (AU)	e	q (AU)	Q (AU)	i
2000 EC ₉₈	10.759	0.455	5.86	15.65	4.3°
2002 UX ₂₅	42.600	0.144	36.46	48.73	19.5°

Table 2: Observing circumstances for 2000 EC₉₈ (R: Heliocentric distance (AU); Δ : Geocentric distance (AU); α : phase angle).

UT Date	R	Δ	α	Telescope
2001 Apr. 26	15.16	14.46	2.81°	NTT
2001 Apr. 27	15.16	14.47	2.86°	NTT
2002 Mar. 18	14.90	13.90	0.11°	Danish
2002 Mar. 19	14.90	13.90	0.18°	Danish
2002 Mar. 23	14.89	13.90	0.45°	Danish
2002 Mar. 24	14.89	13.90	0.52°	Danish
2003 Apr. 10	14.50	13.55	1.36°	T 3.6-m
2003 Apr. 11	14.49	13.56	1.42°	T 3.6-m
2003 Apr. 12	14.49	13.56	1.49°	T 3.6-m

Table 3: Observing circumstances for 2002 UX₂₅ (R: Heliocentric distance (AU); Δ : Geocentric distance (AU); α : phase angle). All the observations have been performed with the 2.0-m telescope of Pik Terskol observatory.

UT Date	R	Δ	α
14 Oct. 2003	42.55	41.55	0.10°
16 Oct. 2003	42.55	41.55	0.05°
19 Oct. 2003	42.54	41.55	0.02°
20 Oct. 2003	42.54	41.55	0.04°
22 Oct. 2003	42.54	41.55	0.09°
21 Dec. 2003	42.52	42.11	1.20°
22 Dec. 2003	42.52	42.12	1.21°
23 Dec. 2003	42.52	42.14	1.22°
24 Dec. 2003	42.52	42.15	1.23°

Table 4: Photometric data of 2000 EC₉₈ used for this work, for the R filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames. Some data are the result of the average of two successive measurements, in order to improve their accuracy.

UT Date	MJD	Mag.	UT Date	MJD	Mag.
2001 Avr. 26	025.9804	21.127± 0.039	2003 Apr. 10	739.2386	20.922± 0.028
2001 Avr. 26	025.9943	21.221± 0.039	2003 Apr. 10	739.2577	20.907± 0.027
2001 Avr. 26	025.9997	21.234± 0.038	2003 Apr. 10	739.2718	20.886± 0.030
2001 Avr. 27	026.0051	21.245± 0.039	2003 Apr. 10	739.2838	20.928± 0.029
2001 Avr. 27	026.0105	21.235± 0.037	2003 Apr. 10	739.2927	20.876± 0.029
2001 Avr. 27	026.0159	21.179± 0.039	2003 Apr. 10	739.3068	20.861± 0.029
2001 Avr. 27	026.0298	21.163± 0.038	2003 Apr. 10	739.3150	20.894± 0.032
2001 Avr. 27	026.0352	21.154± 0.037	2003 Apr. 10	739.9794	20.835± 0.070
2001 Avr. 27	026.0406	21.238± 0.038	2003 Apr. 10	739.9883	20.775± 0.066
2001 Avr. 27	026.0460	21.300± 0.038	2003 Apr. 10	739.9973	20.666± 0.063
2001 Avr. 27	026.0515	21.306± 0.037	2003 Apr. 11	740.0079	20.665± 0.064
2002 Mar. 18	351.2489	20.728± 0.104	2003 Apr. 11	740.0171	20.731± 0.064
2002 Mar. 18	351.2593	20.536± 0.102	2003 Apr. 11	740.0261	20.685± 0.063
2002 Mar. 18	351.2951	20.598± 0.104	2003 Apr. 11	740.0406	20.677± 0.063
2002 Mar. 18	351.3051	20.579± 0.105	2003 Apr. 11	740.0496	20.669± 0.063
2002 Mar. 18	351.3152	20.746± 0.112	2003 Apr. 11	740.0591	20.694± 0.063
2002 Mar. 18	351.3246	20.514± 0.105	2003 Apr. 11	740.0719	20.709± 0.063
2002 Mar. 18	351.3345	20.460± 0.101	2003 Apr. 11	740.0809	20.775± 0.063
2002 Mar. 18	351.3439	20.576± 0.104	2003 Apr. 11	740.1040	20.851± 0.064
2002 Mar. 19	352.2642	20.710± 0.114	2003 Apr. 11	740.1129	20.831± 0.063
2002 Mar. 19	352.2736	20.785± 0.107	2003 Apr. 11	740.1219	20.829± 0.063
2002 Mar. 19	352.3086	20.747± 0.112	2003 Apr. 11	740.1495	20.798± 0.063
2002 Mar. 19	352.3180	20.752± 0.110	2003 Apr. 11	740.1585	20.864± 0.063
2002 Mar. 19	352.3285	20.708± 0.110	2003 Apr. 11	740.1797	20.880± 0.064
2002 Mar. 19	352.3379	20.672± 0.105	2003 Apr. 11	740.1889	20.857± 0.063
2002 Mar. 23	356.2255	20.718± 0.113	2003 Apr. 11	740.1979	20.957± 0.063
2002 Mar. 23	356.2349	20.980± 0.131	2003 Apr. 11	740.2068	20.948± 0.063
2002 Mar. 23	356.2607	20.728± 0.114	2003 Apr. 11	740.2297	20.849± 0.062
2002 Mar. 23	356.2701	20.717± 0.115	2003 Apr. 11	740.2386	20.870± 0.062
2002 Mar. 23	356.2801	20.745± 0.121	2003 Apr. 11	740.2536	20.904± 0.063
2002 Mar. 23	356.2895	20.665± 0.115	2003 Apr. 11	740.2634	20.992± 0.063
2002 Mar. 23	356.2993	20.791± 0.115	2003 Apr. 11	740.2733	21.060± 0.064
2002 Mar. 23	356.3087	20.656± 0.112	2003 Apr. 11	740.2867	21.053± 0.064
2002 Mar. 23	356.3189	20.827± 0.120	2003 Apr. 11	740.3116	20.904± 0.064
2002 Mar. 23	356.3283	20.874± 0.123	2003 Apr. 11	740.9835	20.866± 0.045
2002 Mar. 23	356.3379	20.690± 0.124	2003 Apr. 11	740.9931	20.828± 0.045
2002 Mar. 23	356.3473	20.769± 0.124	2003 Apr. 12	741.0021	20.790± 0.044
2002 Mar. 24	357.2225	21.023± 0.127	2003 Apr. 12	741.0206	20.724± 0.040
2002 Mar. 24	357.2319	20.847± 0.127	2003 Apr. 12	741.0282	20.815± 0.040
2002 Mar. 24	357.2416	20.757± 0.118	2003 Apr. 12	741.0350	20.749± 0.039
2002 Mar. 24	357.2510	20.844± 0.112	2003 Apr. 12	741.0452	20.773± 0.039
2002 Mar. 24	357.2774	20.916± 0.115	2003 Apr. 12	741.0567	20.764± 0.040
2002 Mar. 24	357.2868	20.811± 0.109	2003 Apr. 12	741.0631	20.719± 0.041
2002 Mar. 24	357.2968	20.902± 0.124	2003 Apr. 12	741.0696	20.765± 0.039
2002 Mar. 24	357.3062	20.870± 0.117	2003 Apr. 12	741.0772	20.765± 0.037
2002 Mar. 24	357.3160	20.797± 0.117	2003 Apr. 12	741.1141	20.721± 0.038
2002 Mar. 24	357.3254	20.898± 0.123	2003 Apr. 12	741.1249	20.726± 0.038
2003 Apr. 10	739.0125	20.815± 0.032	2003 Apr. 12	741.1485	20.703± 0.037
2003 Apr. 10	739.0303	20.832± 0.029	2003 Apr. 12	741.1596	20.747± 0.037
2003 Apr. 10	739.0444	20.840± 0.030	2003 Apr. 12	741.1675	20.750± 0.037
2003 Apr. 10	739.0533	20.840± 0.030	2003 Apr. 12	741.1783	20.825± 0.037
2003 Apr. 10	739.0636	20.866± 0.030	2003 Apr. 12	741.1986	20.746± 0.041
2003 Apr. 10	739.0739	20.855± 0.030	2003 Apr. 12	741.2095	20.774± 0.037
2003 Apr. 10	739.0957	20.838± 0.029	2003 Apr. 12	741.2313	20.673± 0.038
2003 Apr. 10	739.1176	20.904± 0.028	2003 Apr. 12	741.2422	20.761± 0.037
2003 Apr. 10	739.1342	20.938± 0.029	2003 Apr. 12	741.2500	20.812± 0.037
2003 Apr. 10	739.1506	20.996± 0.030	2003 Apr. 12	741.2609	20.820± 0.036
2003 Apr. 10	739.1650	20.968± 0.029	2003 Apr. 12	741.2704	20.861± 0.037
2003 Apr. 10	739.1793	20.960± 0.028	2003 Apr. 12	741.2814	20.822± 0.037
2003 Apr. 10	739.1883	20.913± 0.027	2003 Apr. 12	741.2956	20.910± 0.037
2003 Apr. 10	739.1974	20.941± 0.028	2003 Apr. 12	741.3078	20.851± 0.038
2003 Apr. 10	739.2095	20.942± 0.029	2003 Apr. 12	741.3157	20.882± 0.038
2003 Apr. 10	739.2215	20.920± 0.028			

Table 5: Photometric data of 2000 EC₉₈ used for this work, for the V filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames. Some data are the result of the average of two successive measurements, in order to improve their accuracy.

UT Date	MJD	Mag.
2002 Mar. 18	351.2541	21.333± 0.084
2002 Mar. 18	351.3004	21.180± 0.086
2002 Mar. 18	351.3199	21.491± 0.102
2002 Mar. 18	351.3392	21.453± 0.100
2002 Mar. 19	352.2689	21.468± 0.103
2002 Mar. 19	352.3332	21.335± 0.100
2002 Mar. 23	356.2302	21.228± 0.105
2002 Mar. 23	356.2654	21.270± 0.107
2002 Mar. 23	356.2848	21.338± 0.113
2002 Mar. 23	356.3040	21.265± 0.116
2002 Mar. 23	356.3236	21.083± 0.107
2002 Mar. 23	356.3426	21.390± 0.123
2002 Mar. 24	357.2821	21.265± 0.107
2002 Mar. 24	357.3015	21.400± 0.114
2002 Mar. 24	357.3207	21.562± 0.127
2003 Apr. 10	739.0303	21.383± 0.040
2003 Apr. 10	739.0533	21.439± 0.039
2003 Apr. 10	739.0739	21.410± 0.042
2003 Apr. 10	739.1176	21.405± 0.039
2003 Apr. 10	739.1506	21.495± 0.037
2003 Apr. 10	739.1793	21.430± 0.035
2003 Apr. 10	739.1974	21.404± 0.034
2003 Apr. 10	739.2215	21.450± 0.034
2003 Apr. 10	739.2577	21.441± 0.038
2003 Apr. 10	739.2883	21.411± 0.039
2003 Apr. 10	739.9838	21.194± 0.065
2003 Apr. 11	740.0026	21.158± 0.057
2003 Apr. 11	740.0216	21.123± 0.056
2003 Apr. 11	740.0451	21.090± 0.056
2003 Apr. 11	740.0653	21.183± 0.056
2003 Apr. 11	740.0925	21.171± 0.055
2003 Apr. 11	740.1357	21.323± 0.057
2003 Apr. 11	740.1691	21.278± 0.056
2003 Apr. 11	740.1934	21.352± 0.056
2003 Apr. 11	740.2183	21.365± 0.052
2003 Apr. 11	740.2635	21.414± 0.054
2003 Apr. 11	740.2823	21.466± 0.054
2003 Apr. 12	741.0028	21.480± 0.074
2003 Apr. 12	741.0297	21.352± 0.065
2003 Apr. 12	741.0580	21.377± 0.064
2003 Apr. 12	741.0938	21.332± 0.061
2003 Apr. 12	741.1368	21.303± 0.061
2003 Apr. 12	741.1635	21.342± 0.060
2003 Apr. 12	741.1939	21.231± 0.060
2003 Apr. 12	741.2367	21.325± 0.060
2003 Apr. 12	741.2554	21.348± 0.059
2003 Apr. 12	741.2759	21.415± 0.058
2003 Apr. 12	741.3017	21.366± 0.059
2003 Apr. 12	741.3157	21.467± 0.085

Table 6: Photometric data of 2000 EC₉₈ used for this work, for the B filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames. Some data are the result of the average of two successive measurements, in order to improve their accuracy.

UT Date	MJD	Mag.
2002 Mar. 18	351.2645	22.144± 0.158
2002 Mar. 18	351.3293	22.049± 0.155
2002 Mar. 18	351.3487	22.585± 0.220
2002 Mar. 23	356.2397	21.809± 0.124
2002 Mar. 23	356.2749	22.158± 0.151
2002 Mar. 23	356.2942	21.939± 0.145
2002 Mar. 23	356.3135	21.998± 0.149
2002 Mar. 23	356.3330	22.412± 0.200
2002 Mar. 24	357.2272	21.881± 0.134
2002 Mar. 24	357.2464	22.074± 0.124
2002 Mar. 24	357.2916	22.264± 0.163
2002 Mar. 24	357.3109	22.392± 0.172

Table 7: Photometric data of 2002 UX₂₅ used for this work, for the R filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames.

UT Date	MJD	Mag.	UT Date	MJD	Mag.
2003 Oct. 14	926.7932	19.576± 0.065	2003 Dec. 22	995.6751	19.848± 0.052
2003 Oct. 14	926.9000	19.508± 0.048	2003 Dec. 22	995.6828	19.857± 0.052
2003 Oct. 14	926.9437	19.545± 0.058	2003 Dec. 22	995.6902	19.798± 0.050
2003 Oct. 14	926.9927	19.483± 0.060	2003 Dec. 22	995.6987	19.835± 0.053
2003 Oct. 15	927.0177	19.664± 0.063	2003 Dec. 22	995.7153	19.835± 0.050
2003 Oct. 16	928.7526	19.597± 0.052	2003 Dec. 22	995.7230	19.729± 0.049
2003 Oct. 16	928.7574	19.483± 0.052	2003 Dec. 22	995.7318	19.743± 0.047
2003 Oct. 19	931.8688	19.515± 0.032	2003 Dec. 22	995.7395	19.683± 0.052
2003 Oct. 19	931.8812	19.500± 0.033	2003 Dec. 22	995.7513	19.762± 0.051
2003 Oct. 19	931.8929	19.455± 0.036	2003 Dec. 22	995.7598	19.714± 0.050
2003 Oct. 19	931.9035	19.512± 0.037	2003 Dec. 22	995.7983	19.555± 0.051
2003 Oct. 19	931.9115	19.487± 0.034	2003 Dec. 22	995.8058	19.561± 0.051
2003 Oct. 19	931.9196	19.523± 0.035	2003 Dec. 22	995.8136	19.598± 0.048
2003 Oct. 20	932.0136	19.448± 0.052	2003 Dec. 22	995.8212	19.727± 0.049
2003 Oct. 20	932.0214	19.548± 0.059	2003 Dec. 22	995.8509	19.690± 0.055
2003 Oct. 20	932.0289	19.412± 0.111	2003 Dec. 22	995.8703	19.591± 0.056
2003 Oct. 20	932.7919	19.609± 0.038	2003 Dec. 22	995.8780	19.774± 0.057
2003 Oct. 20	932.7995	19.503± 0.039	2003 Dec. 23	996.6380	19.778± 0.063
2003 Oct. 20	932.8077	19.550± 0.040	2003 Dec. 23	996.6457	19.823± 0.057
2003 Oct. 20	932.8152	19.491± 0.041	2003 Dec. 23	996.6531	19.838± 0.051
2003 Oct. 20	932.8226	19.519± 0.040	2003 Dec. 23	996.6613	19.801± 0.055
2003 Oct. 20	932.9391	19.527± 0.039	2003 Dec. 23	996.6699	19.737± 0.057
2003 Oct. 20	932.9465	19.665± 0.040	2003 Dec. 23	996.6848	19.735± 0.063
2003 Oct. 20	932.9543	19.488± 0.042	2003 Dec. 23	996.6948	19.719± 0.068
2003 Oct. 20	932.9745	19.555± 0.040	2003 Dec. 23	996.7140	19.762± 0.051
2003 Oct. 20	932.9819	19.621± 0.047	2003 Dec. 23	996.7216	19.775± 0.058
2003 Oct. 20	932.9938	19.654± 0.042	2003 Dec. 23	996.7325	19.742± 0.061
2003 Oct. 21	933.0090	19.639± 0.041	2003 Dec. 23	996.7426	19.826± 0.058
2003 Oct. 22	934.8408	19.766± 0.044	2003 Dec. 23	996.7502	19.776± 0.057
2003 Oct. 22	934.8577	19.709± 0.041	2003 Dec. 23	996.7584	19.810± 0.067
2003 Oct. 22	934.8733	19.598± 0.041	2003 Dec. 23	996.7661	19.842± 0.074
2003 Oct. 22	934.9004	19.602± 0.041	2003 Dec. 23	996.7736	19.657± 0.057
2003 Oct. 22	934.9506	19.529± 0.046	2003 Dec. 23	996.7815	19.750± 0.058
2003 Oct. 22	934.9708	19.484± 0.057	2003 Dec. 23	996.7891	19.831± 0.058
2003 Oct. 22	934.9758	19.511± 0.054	2003 Dec. 23	996.8039	19.790± 0.061
2003 Oct. 22	934.9805	19.411± 0.048	2003 Dec. 23	996.8115	19.938± 0.058
2003 Oct. 23	935.0140	19.579± 0.066	2003 Dec. 24	997.6435	19.801± 0.053
2003 Oct. 23	935.0189	19.576± 0.061	2003 Dec. 24	997.6515	19.763± 0.052
2003 Oct. 23	935.0249	19.509± 0.060	2003 Dec. 24	997.6604	19.706± 0.048
2003 Oct. 23	935.0299	19.426± 0.073	2003 Dec. 24	997.6685	19.826± 0.054
2003 Oct. 23	935.0348	19.507± 0.087	2003 Dec. 24	997.6778	19.810± 0.049
2003 Oct. 23	935.0397	19.460± 0.082	2003 Dec. 24	997.6859	19.739± 0.052
2003 Dec. 21	994.6501	19.890± 0.061	2003 Dec. 24	997.6937	19.745± 0.051
2003 Dec. 21	994.6579	19.816± 0.062	2003 Dec. 24	997.7036	19.715± 0.050
2003 Dec. 21	994.6659	19.824± 0.060	2003 Dec. 24	997.7112	19.850± 0.054
2003 Dec. 21	994.6734	19.672± 0.056	2003 Dec. 24	997.7189	19.814± 0.052
2003 Dec. 21	994.6811	19.789± 0.059	2003 Dec. 24	997.7264	19.838± 0.048
2003 Dec. 21	994.6896	19.877± 0.055	2003 Dec. 24	997.7339	19.833± 0.056
2003 Dec. 21	994.6971	19.705± 0.056	2003 Dec. 24	997.7419	19.734± 0.054
2003 Dec. 21	994.7079	19.793± 0.054	2003 Dec. 24	997.7498	19.823± 0.049
2003 Dec. 21	994.7158	19.756± 0.052	2003 Dec. 24	997.7575	19.767± 0.047
2003 Dec. 21	994.7239	19.799± 0.053	2003 Dec. 24	997.7667	19.850± 0.051
2003 Dec. 21	994.7314	19.812± 0.053	2003 Dec. 24	997.7743	19.838± 0.050
2003 Dec. 21	994.7405	19.709± 0.051	2003 Dec. 24	997.7818	19.866± 0.055
2003 Dec. 21	994.7484	19.752± 0.054	2003 Dec. 24	997.7892	19.796± 0.052
2003 Dec. 21	994.7588	19.815± 0.054	2003 Dec. 24	997.7976	19.820± 0.052
2003 Dec. 21	994.7668	19.777± 0.056	2003 Dec. 24	997.8056	19.609± 0.050
2003 Dec. 21	994.8186	19.633± 0.051	2003 Dec. 24	997.8129	19.742± 0.050
2003 Dec. 21	994.8381	19.692± 0.052	2003 Dec. 24	997.8204	19.728± 0.050
2003 Dec. 21	994.8643	19.730± 0.055	2003 Dec. 24	997.8277	19.808± 0.053
2003 Dec. 21	994.8720	19.697± 0.059	2003 Dec. 24	997.8444	19.734± 0.052
2003 Dec. 22	995.6446	19.942± 0.053	2003 Dec. 24	997.8518	19.795± 0.055
2003 Dec. 22	995.6600	19.880± 0.052	2003 Dec. 24	997.8821	19.691± 0.058
2003 Dec. 22	995.6677	19.984± 0.052			

Table 8: Photometric data of 2002 UX₂₅ used for this work, for the V filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames.

UT Date	MJD	Mag.
2003 Oct. 14	926.8712	20.204± 0.085
2003 Oct. 22	934.8509	20.336± 0.069
2003 Oct. 22	934.9979	20.322± 0.107
2003 Dec. 21	994.8283	20.206± 0.041
2003 Dec. 22	995.8343	20.200± 0.054
2003 Dec. 22	995.8423	20.274± 0.059

Table 9: Photometric data of 2002 UX₂₅ used for this work, for the B filter. MJD represents the Modified Julian Date - 52000 and is given for mid-frames.

UT Date	MJD	Mag.
2003 Oct. 22	934.8672	21.141± 0.102
2003 Dec. 21	994.8471	21.640± 0.159
2003 Dec. 21	994.8547	21.276± 0.138
2003 Dec. 22	995.8606	21.582± 0.198

Table 10: H-G scattering parametrization obtained from the phase curve

Object		V	R
2000 EC ₉₈	H	9.55 ± 0.04	9.03 ± 0.01
	G	-0.50 ± 0.35	-0.39 ± 0.08
2002 UX ₂₅	H		3.32 ± 0.01
	G		+0.16 ± 0.18

Table 11: Color indices of 2000 EC₉₈ and 2002 UX₂₅.

Object	B-V	V-R
2000 EC ₉₈	0.76±0.15	0.51 ± 0.09 ($\alpha = 0.1 - 0.5^\circ$) 0.55 ± 0.08 ($\alpha = 1.4 - 1.5^\circ$)
2002 UX ₂₅	1.12 ± 0.26	0.61 ± 0.12

Table 12: Centaurs and TNOs with known lightcurve period.

Object	Class ^a	H (mag.)	P(hr) ^b	Refs
(2060) 1977 UB (Chiron)	Centaur	6.5	5.917813± 0.000007 (DP)	1
(5145) 1992 AD (Pholus)	Centaur	7.0	9.9825± 0.004 (DP)	2
			9.9768±0.001 (DP)	3
(15789) 1993 SC	TNO	6.9	≈7.7 (SP)	4
(15820) 1994 TB	TNO	7.1	6.0 or 7.0 (DP)	5
(19255) 1994 VK ₈	TNO	7.0	7.8, 8.6, 9.4 or 10.4 (DP)	5
(8405) 1995 GO (Asbolus)	Centaur	9.0	8.9351±0.0003 (DP)	6
(32929) 1995 QY ₉	TNO	7.5	≈7.0 (DP)	5
(19308) 1996 TO ₆₆	TNO	4.5	6.25±0.03 (SP)	7,8
1997 CV ₂₉	TNO	7.4	8.0, 11.2 or 15.8 (SP)	9
(33128) 1998 BU ₄₈	Centaur	7.2	9.8 or 12.6 (DP)	10
(52872) 1998 SG ₃₅ (Okyrhoe)	Centaur	11.3	16.6 (DP)	11
(26308) 1998 SM ₁₆₅	TNO	5.8	7.966 (DP)	12
(40314) 1999 KR ₁₆	TNO	5.8	11.858 or 11.680 (DP)	10
(31824) 1999 UG ₅ (Elatus)	Centaur	10.1	13.41±0.04 (SP)	13
(29981) 1999 TD ₁₀	TNO (S)	8.8	15.42±0.04 (DP)	14
			15.382±0.002 (DP)	15
			15.382±0.001 (DP)	16
(38628) 2000 EB ₁₇₃ (Huya)	TNO (?)	4.7	6.68, 6.75 or 6.82 (SP)	14
(60558) 2000 EC ₉₈	Centaur	9.5	26.80±0.04 (DP)	This work
(54598) 2000 QC ₂₄₃ (Bienor)	Centaur	7.6	9.14 (DP)	17
(47932) 2000 GN ₁₇₁	TNO	6.0	8.329±0.005	10
(20000) 2000 WR ₁₀₆ (Varuna)	TNO (?)	3.7	6.3442±0.0002 (DP)	18
			3.1718±0.0001 (SP)	14
(32532) 2001 PT ₁₃ (Thereus)	Centaur	9.0	4.1546±0.0001 (SP)	14
(42355) 2002 CR ₄₆	TNO (S)	7.2	3.66 or 4.35 (SP)	14
(83982) 2002 GO ₉	Centaur	9.1	6.97 or 9.67 (SP)	14
(50000) 2002 LM ₆₀ (Quaoar)	TNO	2.6	17.6788±0.0004 (DP)	19
(73480) 2002 PN ₃₄	TNO (S)	8.2	4.23 or 5.11 (SP)	14
(55636) 2002 TX ₃₀₀	TNO	3.3	7.89±0.03 (SP)	20
(55637) 2002 UX ₂₅	TNO	3.6	14.382 (DP) or 16.782 (DP)	This work

a. For the TNOs “S” is for scattered-disk object.

b. SP: Single-peaked lightcurve assumed. DP: double-peaked lightcurve assumed.

References: (1) Marcialis and Buratti, 1993; (2) Buie and Bus, 1992; (3) Hoffmann *et al.*, 1993; (4) Williams *et al.*, 1995; (5) Romanishin and Tegler, 1999; (6) Davies *et al.*, 1998; (7) Hainaut *et al.*, 2000; (8) Sekiguchi *et al.*, 2002; (9) Chorney and Kavelaars, 2004; (10) Sheppard and Jewitt, 2002; (11) Bauer *et al.*, 2003; (12) Romanishin *et al.*, 2001; (13) Bauer *et al.*, 2002; (14) Ortiz *et al.*, 2003a; (15) Rousselot *et al.*, 2003; (16) Mueller *et al.*, 2004; (17) Ortiz *et al.*, 2002; (18) Jewitt and Sheppard, 2002; (19) Ortiz *et al.*, 2003b; (20) Ortiz *et al.*, 2004;

Figure captions:

Figure 1: Radial profile of 2000 EC₉₈, compared with a reference star. The total integration time is 3.075 hours with a 3.5-m telescope.

Figure 2: Corrected magnitudes of 2000 EC₉₈ in the 3 filters, R (filled circles), V (triangles) and B (diamonds) for the eight different nights of observations available. The time is given in Modified Julian Date - 52000 and is light-time corrected for $\Delta = 1$ A.U..

Figure 3: Corrected magnitudes of 2002 UX₂₅ in the 3 filters, R (filled circles), V (triangles) and B (diamonds) for the nine different nights of observations available. The time is given in Modified Julian Date - 52000 and is light-time corrected for $\Delta = 1$ A.U..

Figure 4: Corrected magnitudes of 2000 EC₉₈ (dots with error bars) for R (filled circles) and V (triangles) filters. The time axis has been folded to display a double-peaked lightcurve with a 26.802 hours period. The magnitudes have been shifted according to the phase effect (see Fig. ??) to all fit on the same curve. The lines are drawn with equation (1) and the best fit parameters for the given period and expansion orders given in the text.

Figure 5: Corrected magnitudes of 2002 UX₂₅ (dots with error bars) for R filter . The time axis has been folded to display a lightcurve with period 16.782 hours. The magnitudes have been shifted according to the phase effect (see Fig. ??) to all fit on the same curve. The line is drawn with equation (1) and the best fit parameters for the given period and expansion orders given in the text.

Figure 6: Mean magnitudes of 2000 EC₉₈ (see equation (1)) for the R (filled circles) and V (triangles) filters obtained with the double-peaked lightcurve with period 26.802 hours (see Fig. ??). The phase curves are compared to their H-G scattering parametrization.

Figure 7: Mean magnitudes of 2002 UX₂₅ (see equation (1)) for the R filter obtained with the 16.782 hours period lightcurve. The phase curve is compared to its H-G scattering parametrization.

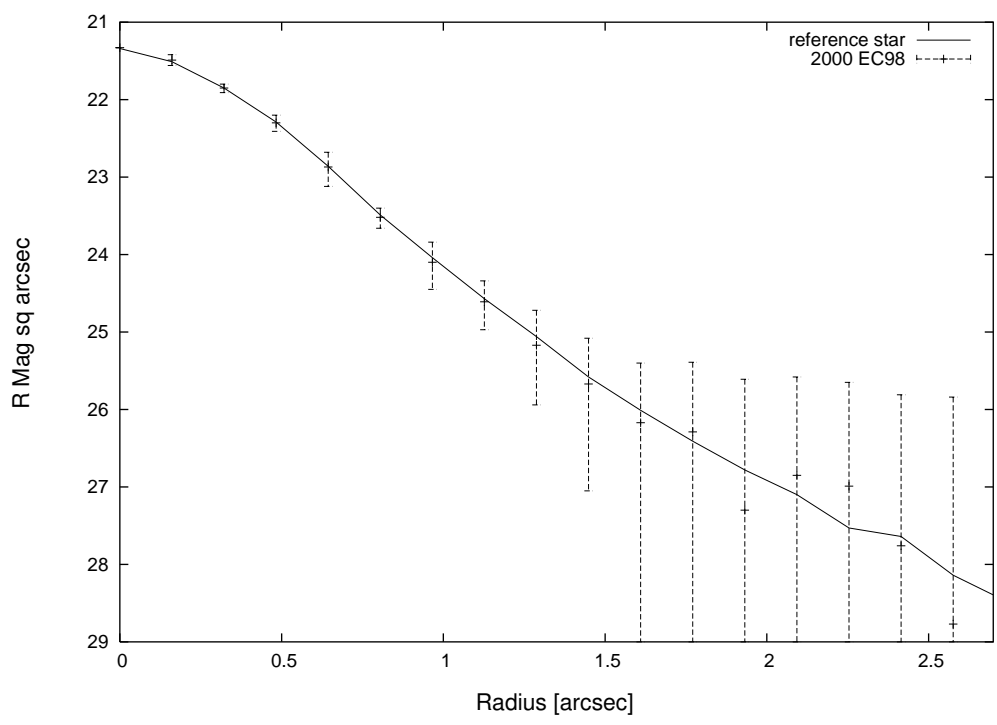


Figure 1:

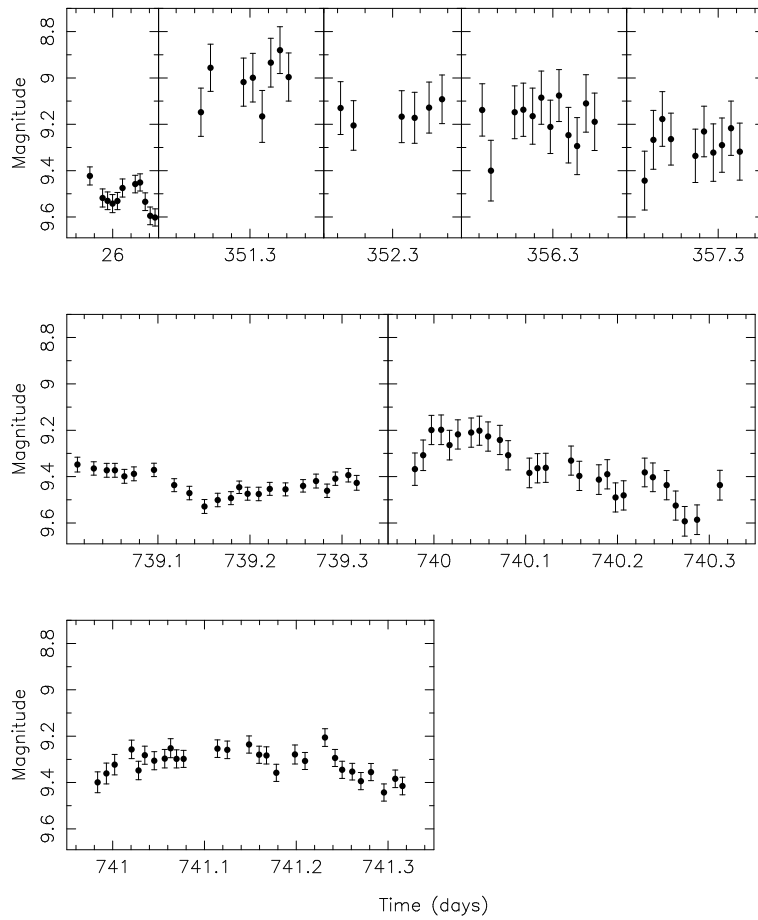


Figure 2:

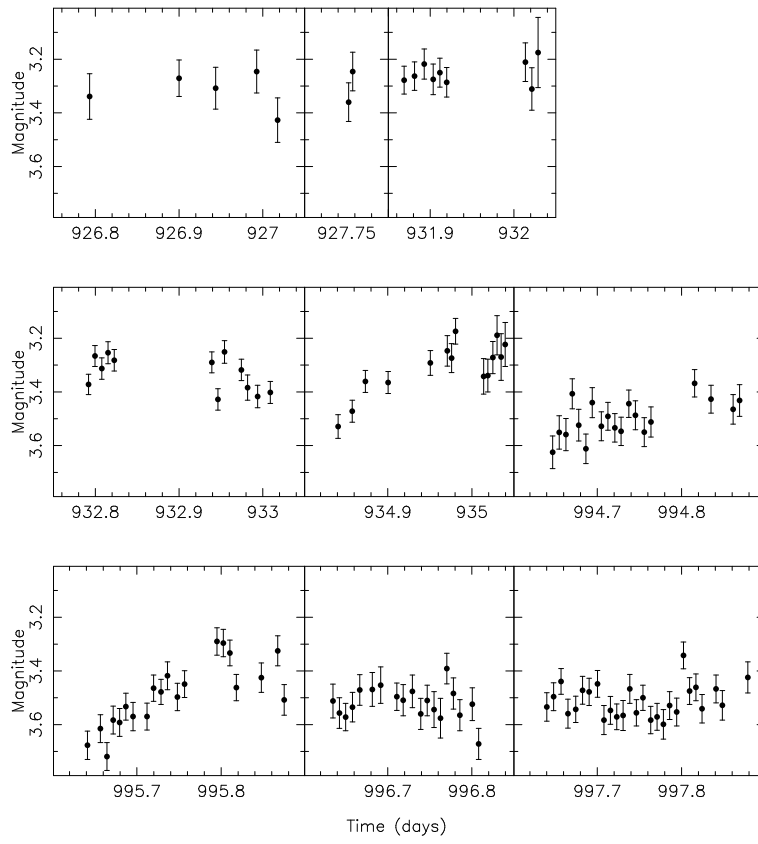


Figure 3:

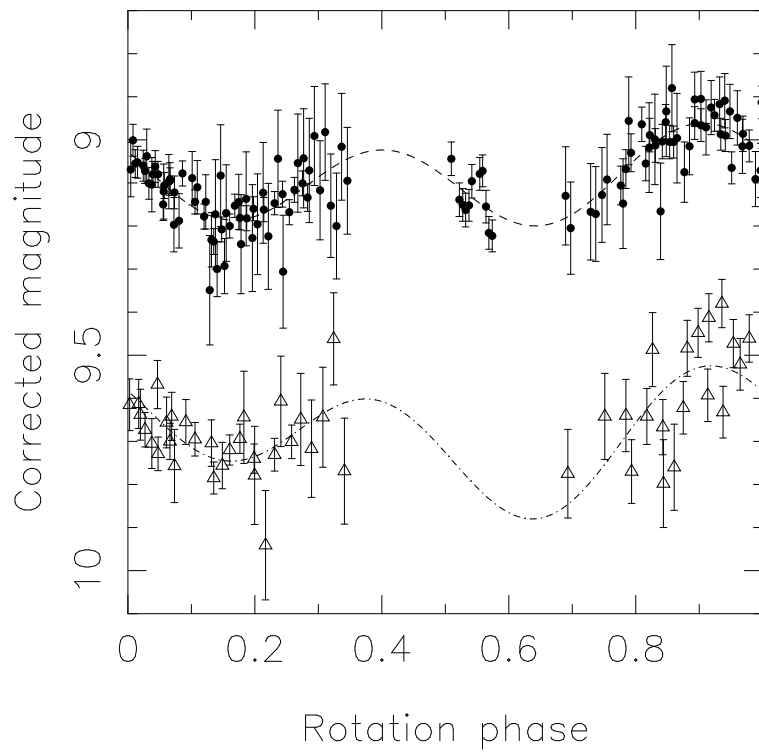


Figure 4:

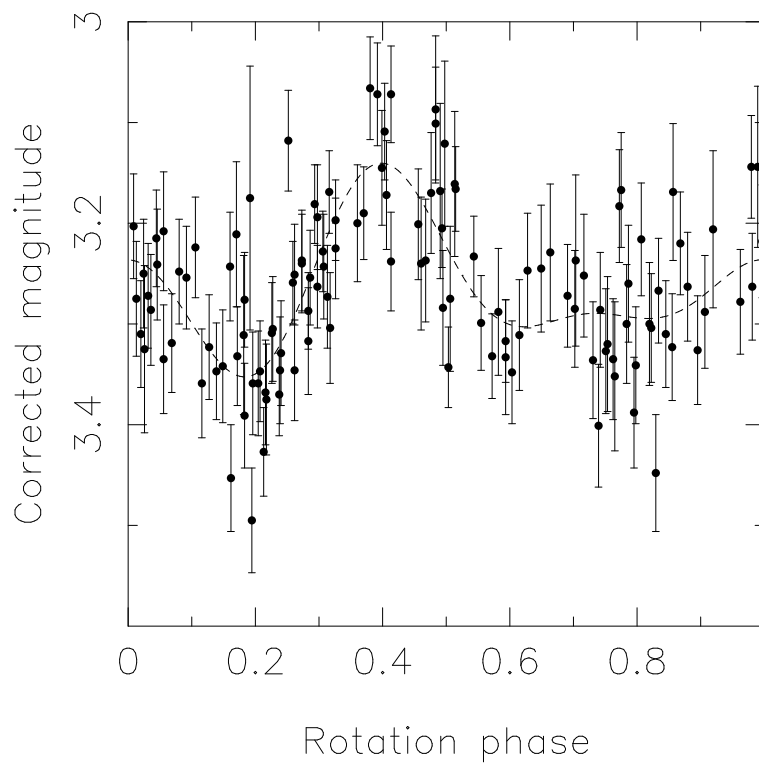


Figure 5:

Phase curve

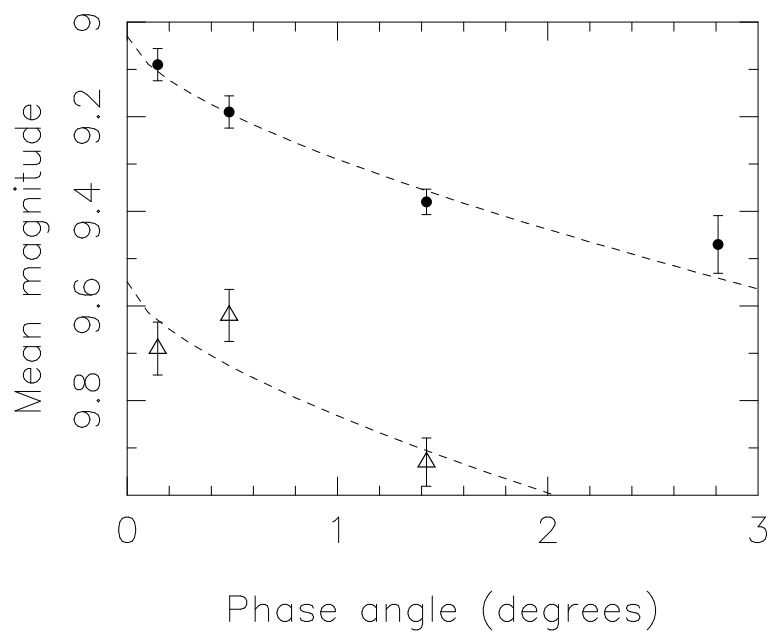


Figure 6:

Phase curve

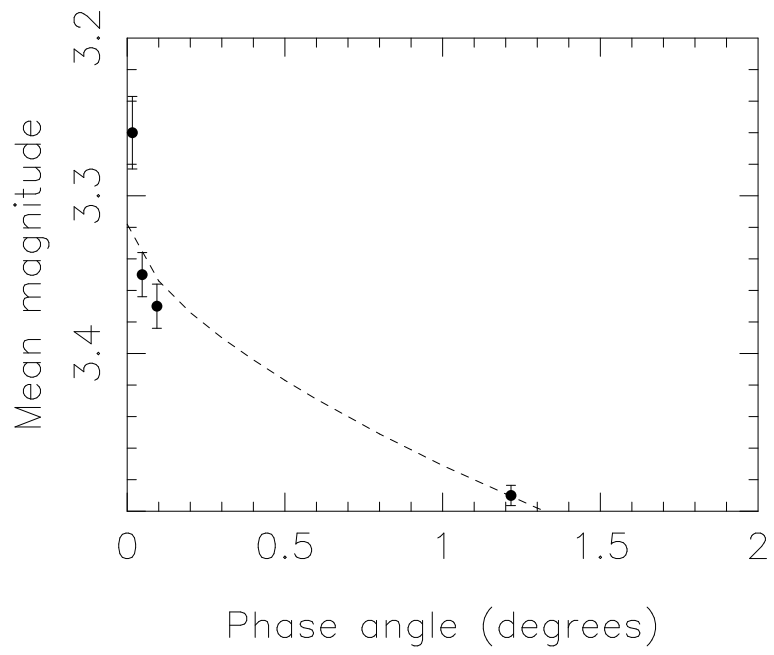


Figure 7: