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Short term variability of Centaur 1999 UG$_5$

P. J. Gutiérrez[1], J. L. Ortiz[1], E. Alexandrino[2], M. Roos–Serote[2], and A. Doressoundiram[3]

[1] Instituto de Astrofísica de Andalucía, CSIC Aptd 3004, 18080 Granada, Spain
[2] Centre for Astronomy and Astrophysics of the University of Lisbon/ Lisbon Astronomical Observatory, Tapada da Ajuda, 1349-018 Lisbon, Portugal
[3] Paris–Meudon Observatory, France

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Abstract. A lightcurve of Centaur 1999 UG$_5$ from R-band CCD images taken at the Calar Alto 1.52 m and La Palma 3.5 m TNG telescopes is presented. The lightcurve shows noticeable changes in brightness. Small activity outbursts do not appear to be the cause of the brightness changes because no coma was detected after coadding all the images. Thus, the changes in brightness are interpreted as being caused by rotational variability. A periodogram analysis of the lightcurve reveals significant peaks from 13.0 h to 13.8 h, with a confidence level exceeding 99.9%. The maximum spectral power corresponds to 13.25 h. The overall shape of the lightcurve can be explained by an irregular object rotating once per 26.5 h, but other possibilities exist. Assuming an ellipsoid shape for the rotating body, the 0.24 ± 0.02 mag amplitude of the lightcurve implies a minimum axial ratio of 1.25. The mean absolute magnitude in V band was found to be $H_V = 10.42 \pm 0.02$ assuming a typical phase parameter $G = 0.15$. This implies a diameter of 55.3 km for the object, provided that a typical albedo of 0.04 is assumed. The colours of 1999 UG$_5$ were found to be $B - V = 0.95 \pm 0.13$, $V - R = 0.63 \pm 0.06$, and $R - I = 0.61 \pm 0.09$.

Key words. minor bodies – Centaurs – photometry – rotation – colours

1. Introduction

Centaurs are thought to be objects that have been injected from the Edgeworth-Kuiper belt to the outer planets domain. They have unstable orbits, with dynamical life times of order of a few million years (e.g. Hahn & Bailey 1990) and can become short period comets. Hence, centaurs are possibly a link between Trans-Neptunian Objects and short period comets, and are therefore important to study. Nevertheless, at the moment, the main problem to carry out the study and characterization of this kind of objects is the fact that only a few centaurs have been identified.

1999 UG$_5$ is one of the most recently discovered centaurs and little is known about this object. At present, some physical properties of this centaur can be determined accurately because it is one of the brightest of its class and, therefore suitable for observation with medium size telescopes. Also, 1999 UG$_5$ can be easily observed spectroscopically with the new generation of large telescopes.

We have carried out photometric observations of 1999 UG$_5$ with the Calar Alto (Spain) 1.52 m telescope with the following objectives:

(1) Determination of a possible rotation period. Knowledge about the rotational state is important for the interpretation of observations that may be carried out in the future. Also, the characterization of the rotational periods of centaurs is important for the understanding of the dynamical evolution and origin of this family of minor bodies;
(2) Search for cometary activity, as was found for Chiron, the largest and brightest of the centaurs (Tholen et al. 1988);
(3) Refinement of the colour indices, which were first determined by Peixinho et al. (2001). They find 1999 UG$_5$ to be one of the reddest objects in the Solar System.

Some R data of 1999 UG$_5$ were also taken during an observing run at the 3.5 m Telescopio Nazionale Galileo (TNG) on La Palma (Spain). Although the run was mainly devoted to TNOs, some time was available to improve the results of the Calar Alto run.

2. Observations and data reduction

2.1. Calar Alto run

The CCD images were obtained during the first three days of a week-long observing run. Due to poor weather, observations could be carried out only from January 19th to January 21st 2001. Seeing oscillated between 2.6 and 1.2 arcsec, the average being around 2.0 arcsec. The CCD

Send offprint requests to: P. J. Gutiérrez,
e-mail: pedroj@iaa.es

Table 1. Photometry of 1999 UG_5. Reduced R mag. Geometric data of the observations are shown in Table 3

Julian date	Exp. (s)	R Mag	Julian date	Exp. (s)	R Mag	Julian date	Exp. (s)	R Mag
2451929.4301	500	10.34	2451930.4841	500	10.28	2451931.4215	500	10.19
2451929.4391	″	10.41	2451930.4908	″	10.22	2451931.4286	″	10.25
2451929.4490	″	10.41	2451930.4975	″	10.23	2451931.4356	″	10.24
2451929.4559	″	10.38	2451930.5039	″	10.29	2451931.4484	″	10.21
2451929.4633	″	10.31	2451931.2715	″	10.45	2451931.4623	″	10.19
2451929.4723	″	10.40	2451931.2790	″	10.44	2451931.4762	″	10.22
2451929.4796	″	10.33	2451931.2927	″	10.41	2451931.4866	″	10.26
2451929.4869	″	10.36	2451931.3003	″	10.43	2451958.3652	100	10.38
2451929.4939	″	10.38	2451931.3081	″	10.37	2451958.3687	300	10.37
2451929.5075	″	10.39	2451931.3152	″	10.43	2451958.3744	″	10.36
2451929.5150	″	10.35	2451931.3220	″	10.35	2451958.3791	″	10.40
2451930.3147	″	10.30	2451931.3362	″	10.36	2451958.3836	″	10.29
2451930.3220	″	10.30	2451931.3427	″	10.40	2451958.3882	600	10.34
2451930.3288	″	10.29	2451931.3496	″	10.40	2451958.4022	″	10.33
2451930.3551	″	10.24	2451931.3565	″	10.34	2451958.4161	″	10.31
2451930.3623	″	10.26	2451931.3655	″	10.30	2451959.3524	″	10.41
2451930.3699	″	10.25	2451931.3726	″	10.30	2451959.3877	360	10.42
2451930.3776	″	10.24	2451931.3793	″	10.25	2451960.3455	600	10.28
2451930.3973	″	10.25	2451931.3862	″	10.27	2451960.3562	″	10.30
2451930.4186	″	10.24	2451931.3928	″	10.26	2451960.3860	360	10.36
2451930.4676	″	10.26	2451931.4068	″	10.20	2451961.3423	″	10.21
2451930.4755	″	10.26	2451931.4147	″	10.27	2451961.3490	″	10.19

detector employed at the 1.52 m telescope was a Tektronix 1024×1024 CCD with an image scale of $\sim$0.4 arcsec/pixel and a 6.9×6.9 arcmin field of view. Standard Johnson BVRI filters were used, but most of the images were taken through the R filter, as the main goal of the observations was to derive a rotation period. The airmass of the observations ranges from 1.07 to 2.1 (2.4 for the first day). Integration times were 500 s.

The reduction of the data was carried out following standard processing of average bias subtraction, flatfield correction (using high signal-to-noise sky flatfields for each filter) and bad pixel removal. The DAOPHOT package was used to get the fluxes of the Centaur and the calibration stars. Two synthetic apertures were used for both the centaur and field stars. Their diameters were 10 and 6 pixels. As is well known, small apertures allow us to improve the signal to noise on faint objects (e.g. Barucci et al. 2000). Thus, as expected, the lightcurve generated with the 6-pixel aperture had a slightly lower dispersion than that generated with the 10-pixel aperture but both had the same shape. The photometry of the centaur was carried out relative to six field stars (observed on all nights) and was placed on an absolute scale by means of observations of the Landolt standard fields pg0231+051 and pg0918+029 (Landolt 1992) for which a large enough aperture to get all the flux was used (30 pixels). The fraction of flux loss in the relatively small apertures used for the centaur and field stars was estimated by measuring the percentage of flux loss on the brightest stars when using apertures of 6, 10 and 30 pixels. The results shown in the present paper have been corrected for this effect. The absolute calibration is uncertain by 0.02 mag.

Table 2. BVI photometry of 1999 UG_5

Julian date	Exp. (s)	Filter	Reduced Mag
24511930.3383	700	V	10.90
24511930.4499	700	V	10.88
24511930.3473	700	I	10.26
24511930.3473	700	I	10.34
24511930.4110	1000	B	11.90
24511930.4384	1000	B	11.87

2.2. La Palma run

CCD images were taken from 17th February to 20th February 2001. The programme was not devoted to 1999 UG_5, but a few R images per night were taken. Average seeing was 1.4 arcsec. The instrument DOLORES was used. The CCD detector was a Loral 2048 by 2048 chip, with a pixel scale of 0.275 arcsec and a total field of view of 9.6 by 9.6 arcmin. Integration times ranged from 300 s to 600 s. The same Landolt fields as for the Calar Alto run were used for calibration.

The reduction was carried out in the same way as that of the Calar Alto run, with the only exception that the apertures were somewhat larger because the pixel scale

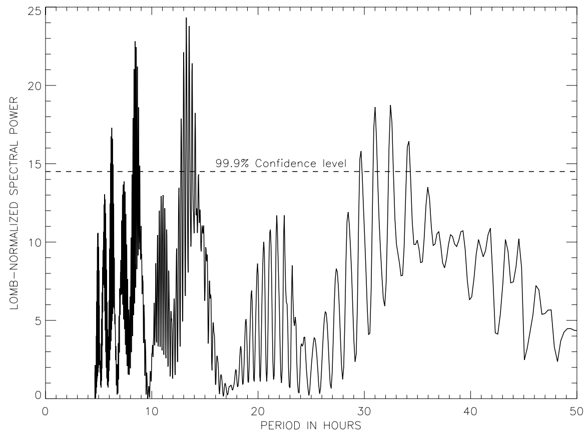

Fig. 1. Lomb normalized spectral power of the lightcurve of 1999 UG_5

was finer in this case. The apertures used had a diameter of 12, 20 and 40 pixels. The absolute calibration is estimated to be uncertain by 0.03 mag.

3. Results and discussion

The 6-pixel aperture Calar Alto R lightcurve of 1999 UG_5, corrected to an aperture of 30-pixel is shown in Table 1. Listed in the same table is the 12-pixel aperture R lightcurve from la Palma, corrected to a 40-pixel aperture. Table 2 summarizes the BVI photometry. In order to correct for the different distances at which the Centaur was observed in the Calar Alto and La Palma runs, the data listed in Tables 1 and 2 were translated into reduced magnitude (magnitude at 1 AU from the Sun and Earth).

The reduced magnitude as a function of time was carefully analyzed to find if any periodicity could be detected. Since the data were unevenly sampled in time, the Lomb method was applied (Lomb 1976) to obtain the periodogram which is shown in Fig. 1. The Lomb periodogram shows a clear peak at 13.25 h with a spectral power of 24.6, which is well above the 99.9% confidence level. Only slightly lower peaks are found at 13.51 h, 8.54 h and 8.42 h and all of them seem good candidates as well. The two latter peaks appear to be aliases of the 13.25 h and 13.51 h periods, because, in frequency, they differ by exactly one cycle per day. The confidence level was estimated as described in Press et al. (1992). Random data substituting the lightcurve data were analyzed with the Lomb technique and the maximum spectral power saved. This was done with 1000 sets of random data in order to get the number of times that the maximum power exceeds the spectral power 23.6. The number of times that this occurred divided by 1000 was our false alarm probability.

Table 3. Geometric data of 1999 UG_5

Date	Julian date	r_{h}(AU)	Δ(AU)	$\alpha(^\circ)$
01/19/01	2451928.5	8.075	7.634	6.42
01/20/01	2451929.5	8.077	7.650	6.46
01/21/01	2451930.5	8.078	7.668	6.51
02/17/01	2451957.5	8.118	8.147	6.96
02/18/01	2451958.5	8.120	8.165	6.95
02/19/01	2451959.5	8.121	8.183	6.94
02/20/01	2451960.5	8.123	8.200	6.92

The lightcurve phased to a period of 13.25 h and 8.42 h is shown in Fig. 2. If an irregular shape for the object is assumed, a periodicity of 13.25 h implies a rotation period of 26.5 h. If the oscillations were due to a distinct and large area of different albedo than the rest of the surface, the 13.25 h photometric period would imply a 13.25 h rotation period. Thus far one cannot definitely conclude what the rotation period is. However, the shape of minor bodies in the size range of ∼50 km (in diameter) is frequently non-spherical and therefore, the changes in cross section as the object rotates are likely the cause for the variability, which argues for the 26.5 h rotation period.

Synthetic lightcurves were generated using the cometary nucleus model described in Gutiérrez et al. (2000) (but slightly adapted to shut down the sublimation processes). Using a period of 26.5 h for several irregular bodies, including a triaxial ellipsoid, with different spin axis orientations, and sampled at the same times as the actual lightcurve, the synthetic power spectra all look similar to the actual lightcurve spectrum of Fig. 1. In Fig. 3, the Lomb spectral power of a synthetic lightcurve of an ellipsoid with an axial ratio of 1.25 and a rotation period of 26.5 h is shown. The synthetic data were sampled at the same Julian dates as the observational data. The similarity of the synthetic spectrum with that in Fig. 1 is readily seen. Using 13.25 h as the rotation period, the real spectrum could not be matched unless a large and bright area (14% of the total area with an albedo 30% higher than the mean albedo) was present in the body.

Another possible explanation for the changes in brightness might be related to sudden activity outbursts. Activity outbursts were observed in Chiron (e.g. Tholen et al. 1988), and have also been called for to explain the anomalous lightcurve of 1996TO_{66} (Hainaut et al. 2000). This could also be the case for 1999 UG_5. However, no coma was present in the Calar Alto images of 1999 UG_5. After coadding all the images recentered on the centaur (totaling more than 7 hours of integration) no coma could be observed. The profiles of the centaur in all directions were essentially indistinguishable from those of nearby stars with the same total integration time (in this case the coaddition was done by recentering on a star close to the Centaur). This appears to rule out any possible explanation of the observed brightness changes in terms of activity outbursts.The size of the coma that would cause a 0.26 mag change on 1999 UG_5 should be detectable in 7-hour integrations, but it was not.

Concerning the colours of 1999 UG_5, the values of $B-V = 0.95 \pm 0.13$, $V-R = 0.63 \pm 0.07$ and $R-I = 0.60 \pm 0.09$ have been found. Therefore, 1999 UG_5 is indeed very red, as pointed out by Peixinho et al. (2001). The colours presented here are essentially in agreement with those by Peixinho et al. (2001) if their error bars and those shown

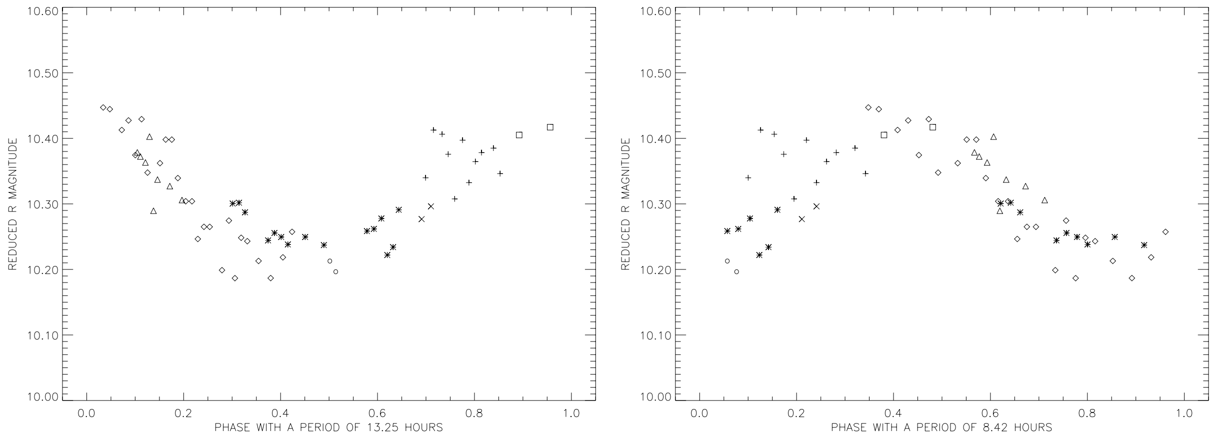

Fig. 2. Left: Phase curve of 1999 UG_5 for a period of 13.25 h. Right: Phase curve for a period of 8.42 h. In both plots, +: Jan. 19-20, ∗: Jan. 20-21, ⋄: Jan. 21-22, △: Feb. 17-18, □: Feb. 18-19, ×: Feb. 19-20, ○: Feb. 20-21. Zero phase is at JD 2451929.0

here are taken into account. More accurate measurements are still needed to refine these values.

The average absolute magnitude H_V is 10.42 ± 0.02 provided that a typical phase parameter $G = 0.15$ is used. This $H_V = 10.42$ can be compared with $H_V = 10.61 \pm 0.07$ found by Peixinho et al. (2001), which was obtained in February 2000. As the phase angle of the centaur was almost equal in both runs, the factor G cannot explain the differences from 2000 to 2001. The 0.19 mag of difference can best be accounted for by the rotational variability. The H_V value implies a diameter of 55.3 km provided that a geometric albedo of 0.04 is assumed (which is typically the value adopted for most cometary nuclei and was also the value derived for Centaur Chariklo by Jewitt & Kalas 1998).

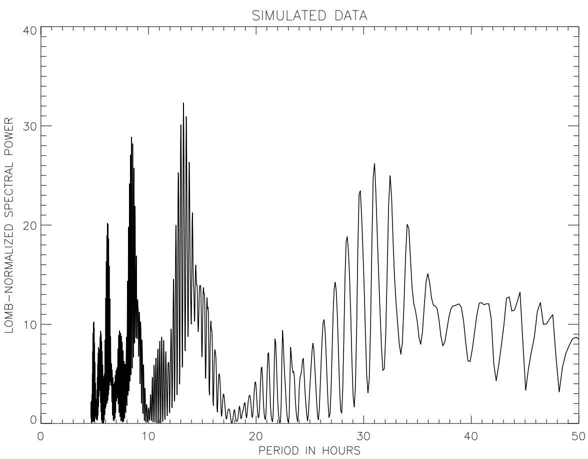

Fig. 3. Lomb normalized spectral power of the synthetic lightcurve of an ellipsoid with an axial ratio of 1.25 spinning with a period of 26.5 h. The synthetic data used in the Lomb analysis correspond to the same UT times as the observations of 1999 UG_5. The period corresponding to the maximum spectral power is 13.25 h

4. Conclusions

From the observations carried out at the Calar Alto 1.52 m and the La Palma 3.5 m TNG telescopes, a lightcurve in R was obtained which shows short term variability with a periodicity of 13.25 h, although 13.51 h, 8.54 h and 8.42 h are also possible. This short term variability can be interpreted as the variation that would be induced by an irregular body rotating once every 26.5 h. Another possible interpretation for the short term variability could be that the variation is caused by an albedo feature on an object that rotates once per 13.25 h. Other possibilities are not ruled out yet. The amplitude of the oscillations can be matched by a rotating ellipsoid whose axis differ by about 25%. The colours of this object are remarkably red, in agreement with Peixinho et al. (2001).

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