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Lightcurves of Centaurs 2000 QC_{243} and 2001 PT_{13}

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Abstract. We present CCD photometric observations of Centaurs 2000 QC_{243} and 2001 PT_{13}. For 2000 QC_{243}, a large amplitude period is found at 4.57 h ± 0.05 h, which likely corresponds to half the rotation period of the body, or coincides with the full rotation period, depending on whether the variability is induced by an irregular shape or by albedo features. The apparent double-peaked lightcurve favors the first interpretation. The large amplitude of the oscillations imply a very irregular shape for this object or a large albedo assymmetry between the two hemispheres. For 2001 PT_{13}, a clear period of 4.15 h ± 0.05 h was detected, with an amplitude of 0.16 mag. Since 4.15 h is close to the breakup limit for typical cometary densities and tensile strengths, 8.3 h appears to be a more likely rotation period.

Key words. minor planets, asteroids – Kuiper Belt

1. Introduction

Currently, there is a growing interest in studying Trans-Neptunian Objects, (TNOs) because these icy bodies are thought to be the most pristine objects in the Solar System. TNOs may give important clues on the origin of the Solar System and of at least a group of short period comets, the Jupiter family comets. Centaurs are thought to be objects which were TNOs originally, but are now in the process of becoming short-period comets as a result of gravitational perturbations by Neptune and the other giant planets, or ejection through collisions in the Kuiper Belt. Their orbits are unstable on a timescale of about 10^6–10^7 years (Levinson & Duncan 1997). Hence, Centaurs are possibly the link between TNOs and short period comets. Yet the number of known Centaurs is still very low in comparison with the large number of TNOs discovered so far. This means that the statistics on the properties of the Centaur population are even poorer than in the case of the TNOs.

Photometry of Centaurs, focused on short term variability has been presented recently by Davies et al. (1998), Peixinho et al. (2001) and Gutiérrez et al. (2001), in which several rotation periods have been derived. For the case of Pholus, not only is the period known but the orientation of the rotation axis has also been determined recently (Farnham 2001). To improve the current data base on Centaurs photometric properties we decided to study two of the brightest ones available, namely 2001 PT_{13} and 2000 QC_{243}. Our main goal was not to derive colors but to study the short term variability and to determine rotation periods. Knowledge on the rotational properties of a large number of objects is important because it can give information about the collisional evolution of the Centaurs. In addition, in order to derive albedos from future infrared observations of these objects (which are well suited for such investigations with the current largest telescopes) a certain knowledge of the rotation properties is needed. Besides, the short term variability is important for Centaurs and TNOs, because such variability must be adequately accounted for in order to derive accurate color photometry. The current work adds two more objects to the list of centaurs whose short term variability has been studied in some detail. 2001 PT_{13} is a remarkably bright object among its class and yet it remained undiscovered until very recently. 2000 QC_{243} is a fainter Centaur, but still well within the detection limits of our instrumentation. To our knowledge, only *BVRI* observations aimed at determining colors have been reported for 2000 QC_{243} (Delsanti et al. 2001). These colors must be adopted with

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Table 1. Observing dates and relevant data.

Object	Date	Ecliptic longitude	Heliocentric distance (AU)	Geocentric distance (AU)	Phase angle (degrees)
2000 QC_{243}					
	2001-Aug.-13	336.9550	19.3043	18.3360	0.9136
	2001-Aug.-15	336.9747	19.3035	18.3258	0.8127
	2001-Aug.-17	336.9944	19.3026	18.3169	0.7108
	2001-Aug.-18	337.0042	19.3022	18.3129	0.6594
	2001-Aug.-19	337.0141	19.3018	18.3091	0.6079
	2001-Aug.-20	337.0239	19.3016	18.3057	0.5561
2001 PT_{13}					
	2001-Sep.-10	333.0884	8.8606	7.9327	2.6680
	2001-Sep.-11	333.1293	8.8613	7.9380	2.7365
	2001-Sep.-12	333.1702	8.8619	7.9436	2.8071
	2001-Sep.-13	333.2110	8.8626	7.9494	2.8793
	2001-Sep.-14	333.2518	8.8633	7.9556	2.9531
	2001-Oct.-23	334.8365	8.8900	8.3796	5.6673
	2001-Oct.-24	334.8769	8.8907	8.3943	5.7146
	2001-Oct.-25	334.9173	8.8914	8.4091	5.7603
	2001-Oct.-26	334.9578	8.8921	8.4241	5.8043
	2001-Oct.-27	334.9982	8.8927	8.4391	5.8468
	2001-Oct.-28	335.0386	8.8935	8.4544	5.8876

some caution in view of the findings reported here, because the rotational variability may have affected those observations.

2. Observations and data reduction

The observations were carried out at the Sierra Nevada Observatory 1.5 m telescope during three separate 1-week runs in August, September and October 2001 (August 13–20, September 10–16, October 23–29). Observing conditions were good most of the nights in each campaign, but clouds prevented the observations during several nights. The list of actual observing dates along with information on the objects on those dates is shown in Table 1. The seeing oscillated between 1.0 arcsec to 2.6 arcsec, the average of each run being around 1.5 arcsec.

The camera used at the 1.5m telescope was a fast readout 1024×1024 CCD based on a Kodak KAF1001E chip with square $\sim$0.41 arcsec pixels and a $7{\times}7$ arcmin field of view. Exposure time was on the order of 100 s. Typical drift rates for these objects were in the order of 0.1 arcsec per 100 s, well below the seeing disc size in our exposures. In order not to waste $\sim$30% of the observing time in CCD readout, we used a fast readout CCD, whose read noise was still significantly lower than the typical shot noise from the sky background.

We used standard Johnson $BVRI$ filters, but most of the data were taken with no filters in order to get the maximum signal to noise ratio possible for the time variability study. Integration times were typically 100 s, in which a signal to noise ratio of approximately 15 was achieved for most of the images. More than one thousand images were obtained and analyzed.

The reduction of the data was carried out following standard processing of average bias subtraction and flat-field correction using high signal-to-noise twilight sky flat-fields for each filter. The DAOPHOT package was used for the synthetic aperture calculations. Several synthetic apertures were used for the objects and field stars. The data presented here are those obtained with the aperture that gave the lowest scatter in the data. This corresponded to a diameter of 12 pixels, which is close to 2 times the full width at half maximum ($FWHM$) of the star profiles in the worst seeing images; 2 times the $FWHM$ is expected to be the optimum aperture to obtain the best signal to noise ratio, as described in Barucci et al. (2000). From the dispersion of the data we estimate that the average error of the 100-s exposures on the Centaurs was 0.06 mag, close to the error expected from theoretical calculations of the signal to noise ratios for these exposures.

The photometry was performed relative to six field stars, observed within the field of view on at least four nights within each run. The relative magnitudes were placed in an absolute scale using observations of Landolt standard star fields (Landolt 1992). The fraction of flux loss in the relatively small 12-pixel apertures was computed by measuring the percentage of flux loss on the brightest stars in the Centaur frames. The final results are therefore corrected for this effect. The absolute calibration was performed using only the best nights in terms of photometric quality.

Since our broadband observations do not correspond to any of the photometric Johnson bands, we expect that

Table 2. Photometry of 2000 QC_{243}, Aug. 2001.

Julian date	R^* mag	Julian date	R^* mag
2452135.49562	21.01	2452140.45977	20.84
2452135.27783	20.38	2452140.47358	20.87
2452135.50993	20.77	2452140.48654	20.62
2452135.52167	20.67	2452140.53253	20.45
2452135.53341	20.57	2452140.54592	20.17
2452135.54336	20.54	2452140.60055	20.34
2452137.44396	20.48	2452140.61104	20.51
2452137.46397	20.37	2452141.42805	20.82
2452137.47473	20.44	2452141.44135	20.70
2452137.48620	20.32	2452141.45500	20.58
2452137.49656	20.22	2452141.46851	20.39
2452137.50660	20.16	2452141.48219	20.31
2452137.51663	20.20	2452141.55650	20.38
2452137.59538	20.70	2452141.56624	20.43
2452137.60374	20.74	2452142.43096	20.37
2452137.63611	20.58	2452142.44474	20.32
2452137.45363	20.41	2452142.45897	20.34
2452137.64485	20.42	2452142.47320	20.27
2452139.46315	20.34	2452142.48556	20.21
2452139.47659	20.48	2452142.54595	20.56
2452139.57793	20.54	2452142.56071	20.64
2452139.63911	20.34	2452142.62078	20.42
2452140.43071	20.80	2452142.63410	20.31
2452140.44680	20.94		

a strong color effect must be present in our data, so we caution the reader that the magnitude plotted and listed in our graphs may be off by even 0.1 mag. For that reason we are referring to our data as R^* rather than R data. This possible systematic bias is important if the presented data are to be compared with data from other investigators. The absolute calibration was carried out in order to be able to estimate the size of the object.

We checked the photometry results by plotting the ratios of the fluxes from several field stars versus time. The standard deviation of these plots never exceeded 0.01 mag, which is highly satisfactory. These ratios were inspected for possible low amplitude short period variability of the field stars themselves, but no variability was detected.

3. Results and discussion

The R^* magnitudes of 2000 QC_{243} and 2001 PT_{13} are listed as a function of time in Tables 2, 3 and 4. Here, the magnitudes as a function of time were binned in steps of 1200 s in order to make the tables of a reasonable length. In other words, the data points with steps of 1200 s were median averaged.

The Lomb periodograms corresponding to 2000 QC_{243} and 2001 PT_{13} were computed using the original unbinned data. The Lomb (Lomb 1976, as described in Press et al. 1992) technique was used because it is a powerful means to search for periodicities when the data are unevenly sampled in time. There are clear periodic signals

Table 3. Photometry of 2001 PT_{13}, Sep. 2001.

Julian date	R^* mag	Julian date	R^* mag
2452163.35257	18.62	2452165.44166	18.78
2452163.36715	18.62	2452165.45635	18.75
2452163.37734	18.57	2452165.52575	18.61
2452163.43874	18.51	2452165.54006	18.64
2452163.45160	18.56	2452165.55376	18.69
2452163.46647	18.65	2452166.41761	18.60
2452163.47541	18.69	2452166.47548	18.66
2452163.55021	18.63	2452166.48518	18.67
2452163.55618	18.59	2452166.53174	18.57
2452163.60052	18.52	2452166.57418	18.57
2452164.38051	18.71	2452167.35102	18.65
2452164.49394	18.61	2452167.36550	18.65
2452164.50608	18.63	2452167.37895	18.59
2452164.57488	18.68	2452167.39329	18.52
2452164.58526	18.66	2452167.47649	18.68
2452165.41453	18.74	2452167.53496	18.68
2452165.42906	18.77	2452167.54586	18.65

Table 4. Photometry of 2001 PT_{13}, Oct. 2001.

Julian date	R^* mag	Julian date	R^* mag
2452206.39219	18.79	2452209.40048	18.90
2452206.40673	18.77	2452209.41494	18.84
2452206.41921	18.81	2452209.42762	18.83
2452206.43355	18.83	2452209.44231	18.79
2452206.44648	18.81	2452209.45662	18.80
2452207.28600	18.85	2452209.46606	18.81
2452208.28085	18.77	2452210.27251	18.85
2452208.29498	18.82	2452210.28744	18.85
2452208.30828	18.90	2452210.30072	18.79
2452208.32284	18.89	2452210.31452	18.76
2452208.33673	18.89	2452210.32485	18.74
2452208.34568	18.86	2452210.34412	18.78
2452209.34388	18.89	2452211.27153	18.94
2452209.35902	18.94	2452211.28545	18.93
2452209.37303	18.93	2452211.29997	18.93
2452209.38676	18.94	2452211.31156	18.95

at 4.57 h $\pm$ 0.05 h and 4.15 h $\pm$ 0.05 h for 2000 QC_{243} and 2001 PT_{13} respectively. The spectral power of these signals are above a 99.9% confidence level. The confidence levels were computed in a similar fashion as described in Gutiérrez et al. (2001). For the case of 2001 PT_{13}, which was observed in two separate runs, both runs gave a periodic signal close to 4.15 h $\pm$ 0.05 h.

The binned data in Tables 2, 3 and 4 have been inspected for periodicity and the results are the same as those obtained with the unbinned data, giving very similar spectra.

Figures 1–2 and 3–6 show the rotational phase plots for 2000 QC_{243} and 2001 PT_{13} respectively, using two different periods (the nominal photometric period and twice that period, in order to check whether the lightcurve is double-peaked or single-peaked). Different symbols for each date have been used in order to show that some

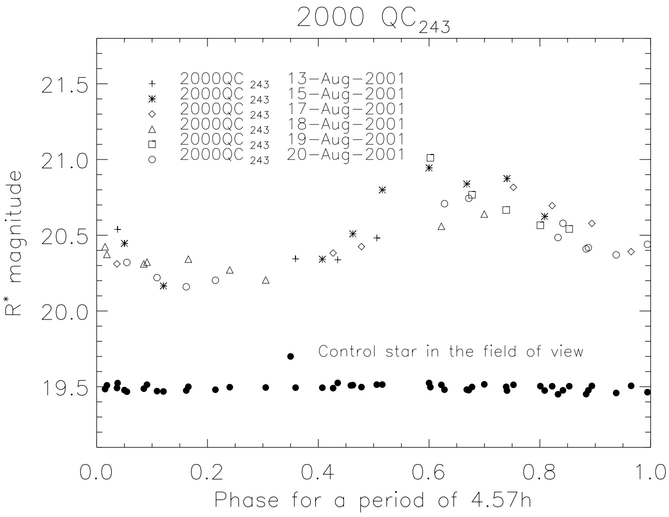

Fig. 1. Rotational phase plot of 2000 QC_{243} using a period of 4.57 h. The data from different days are plotted with different simbols. The magnitude of a control star present in the same images as the object is also plotted in order to emphasize the fact that the oscillation in the brightness of 2000 QC_{243} are real and not reduction artifacts.

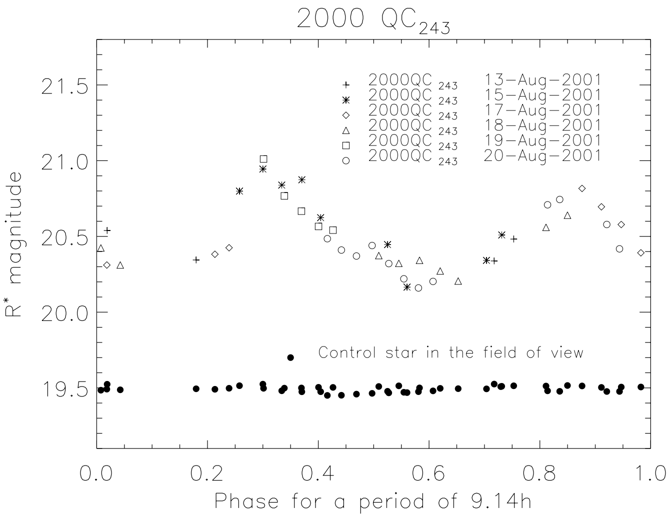

Fig. 2. Same as Fig. 1, but for a period of 9.14 h. The 9.14 h period appears to be the real rotation period, as the lightcurve seems to be double-peaked.

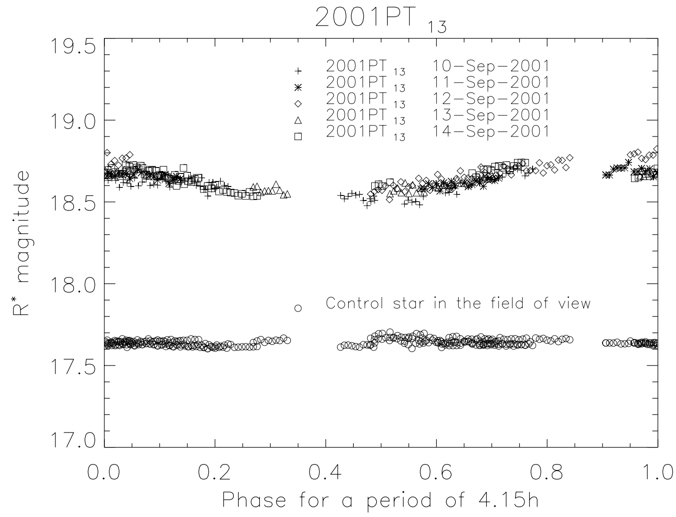

Fig. 3. Rotational phase plot of 2001 PT_{13} for the data obtained in September 2001, using a period of 4.15 h. The data from different days are plotted with different simbols. The magnitude of a control star present in the same images as the object is also plotted in order to emphasize the fact that the oscillation in the brightness of 2001 PT_{13} are real and not reduction artifacts.

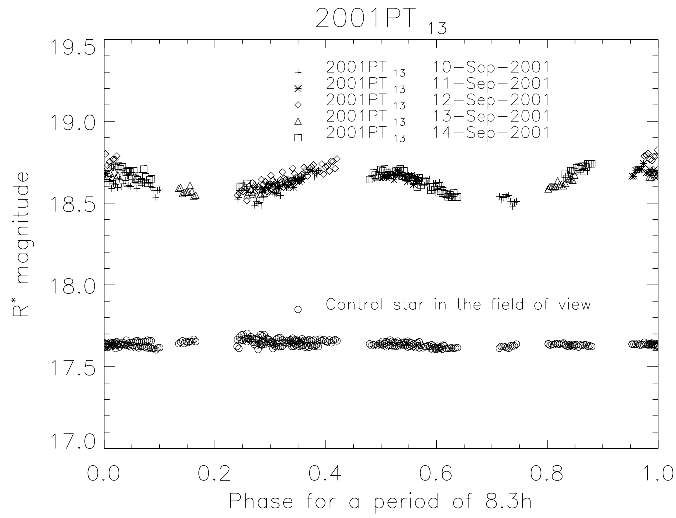

Fig. 4. Same as Fig. 3 for the data obtained in September 2001, using a period of 8.3 h.

phases of the lightcurves were observed on several nights. The magnitude of a control star present in the same field as the objects during at least four days within each run has been plotted, in order to check that the centaurs brightness variations are real and are not artifacts from the reduction.

The mean size of 2000 QC_{243} (obtained by taking the mean of the periodic signal of Fig. 3) is 99 ± 5 km in radius, by assuming a geometric albedo of 0.04 and no orbital phase correction.

As can be seen, the lightcurve of 2000 QC_{243} appears to be double-peaked for a rotation period of 9.14 h, although a single peaked 4.57-h lightcurve cannot be entirely ruled out. The peak to peak amplitude is large, close to 0.7 mag, which suggests that the object is highly irregular with an axial ratio of approximately 1.9 or even higher if the rotation axis is not nearly perpendicular to the Earth-Sun-Object plane. Such an irregular outer solar system object for the above mentioned size is somewhat surprising, although there are very irregular moons as well as very irregular trojan asteroids and TNOs like 1999 TD_{10} whose shape also appears to be very irregular (Consolmagno et al. 2000).

An extremely large albedo variation would be required to explain such a large amplitude, which is highly

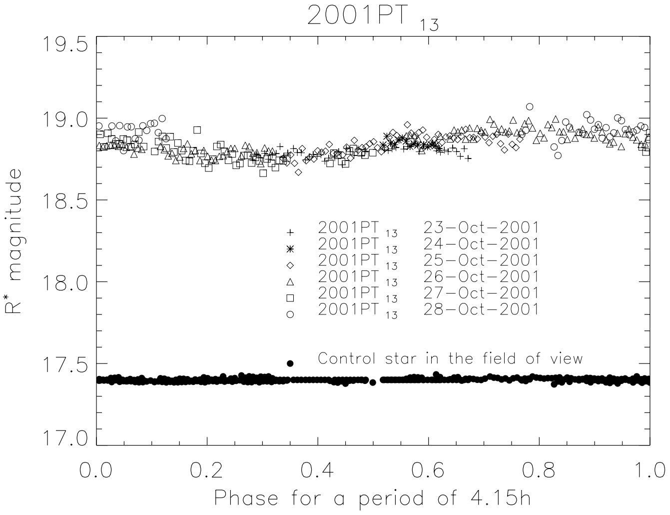

Fig. 5. Same as Fig. 3 for the data obtained in October 2001, using a period of 4.15 hours.

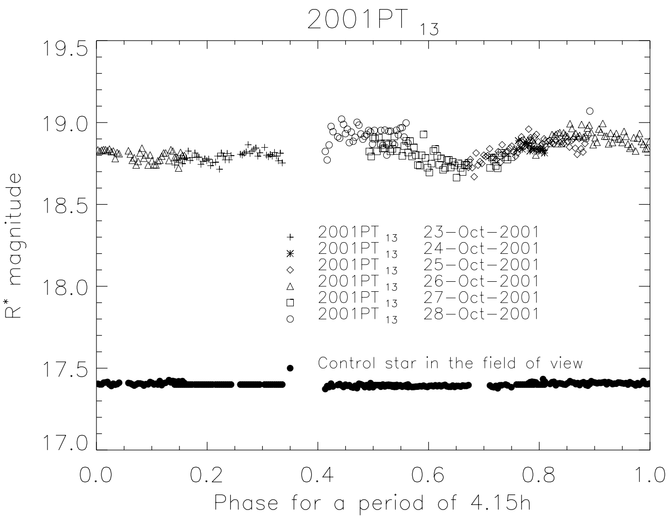

Fig. 6. Same as Fig. 3 for the data obtained in October 2001, using a period of 8.3 hours.

unlikely, but cannot be ruled out entirely as there are other Solar System objects with large albedo asymmetries; if one assumes that one hemisphere has an albedo of 0.04, the other hemisphere would have to be more than two times brighter, with an albedo of 0.09. Alternatively, a very reflective and large spot would be required to explain the observed variations in the lightcurve. However, a rotation rate of only 4.57 h for an object the size of 2000 QC_{243} is close to the critical limit of rotational breakup for typical cometary tensile strengths and densities.

Concerning the much brighter Centaur 2001 PT_{13}, brightness variations due to albedo features are again difficult to reconcile with the fact that the object would be near the critical rotation breakup limit. Therefore, a rotation period of 8.3 h is more likely.

Other causes for variability in Centaurs might be sudden activity outburts, but these would be random, not periodic; therefore, activity outbursts cannot explain the observed variability. Activity outburst leading to a coma have been observed in Chiron (e.g. Tholen et al. 1988), and activity outbursts have been reported for TNO 1999 TO_{66} (Hainaut et al. 2000), but this was not the case for Centaurs 2000 QC_{243}, and 2000 PT_{13}, at least during our observing periods. No sign of a coma was detected in our images.

Another cause for variability could be a binary or multiple nature of these objects. Eclipsing binaries can indeed generate lightcurves. Binary or multiple objects may not be too unusual, since at least four such binaries have been detected in the Kuiper Belt (Veillet et al. 2001; Elliot 2001; Kavelaars et al. 2001; Trujillo & Brown 2001), apart from the Pluto-Charon system. If binaries or multiple systems are very common, then the interpretation of the lightcurves may not be as simple as proposed here, because two or several periodicities may be superimposed. Therefore, the variability induced by a binary system cannot be ruled out, although it seems less likely than the variability induced by irregular shape or albedo variations across the disk.

4. Conclusions

From the lightcurves presented in this study, confident periodic signals of 4.57 h and 4.15 h have been found for 2000 QC_{243}, and 2000 PT_{13} respectively. These are preferentially interpreted as half the rotation period, although other possibilities that have been discussed cannot be ruled out yet. The large amplitude of the oscillations in the lightcurve of 2000 QC_{243} tends to suggest either a very irregular shape for a large object (which is remarkable but conceivable), or a large albedo constrast, or a combination of both. Also, the object might be a binary. For the case of 2000 PT_{13} the amplitude of the lightcurve is lower, which seems to indicate a less irregular body.

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