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Rotational brightness variations in Trans-Neptunian Object 50000 Quaoar

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Abstract. Time–resolved broad–band CCD photometry of Trans-Neptunian Object 50000 Quaoar carried out using the 1.5 m telescope at Sierra Nevada Observatory is presented. The lightcurve reveals short–term variability due to rotation of the body. The periodogram analysis shows a peak at 8.8394 ± 0.0002 h with a confidence level above 99.9%. The lightcurve seems to be double–peaked, and therefore the rotation period would be 17.6788 ± 0.0004 h. The amplitude of the oscillation is 0.133 ± 0.028 mag. Under the assumption that the rotational variation is induced by an irregular shape, the minimum axial ratio of Quaoar would then be 1.133 ± 0.028.

Key words. minor planets, asteroids – Kuiper Belt

1. Introduction

50000 Quaoar (2002 LM_{60}) was discovered on June 4th, 2002 from the Palomar Observatory 48-inch Oschin telescope (Williams et al. 2002). Its remarkable brightness soon indicated that it could be one of the largest Trans-Neptunian Objects (TNOs) discovered so far, or its albedo could be abnormally high. By using disk–resolved images from HST, Brown & Trujillo (2002) estimated that the diameter of Quaoar is 1260 ± 190 km. This revealed that Quaoar is actually the largest of all known TNOs except for Pluto, and also the largest currently known minor planet. Given its size, Quaoar is one of the most suitable targets to be observed and studied in depth from the ground. For example, Quaoar is a bright enough target for spectroscopic observations by means of large telescopes.

In order to correctly interpret many of the potential observations of Quaoar, or to suitably model the data obtained, it is important to know its spin period. For example, some knowledge of the rotation period is needed in order to apply correct thermophysical models to interpret thermal observations. Also, precise knowledge on the rotation period can provide the link needed to check possible heterogeneity of its surface as may be revealed by spectroscopy. In addition, the analysis of the short–term variability can provide necessary information to determine how irregular the body is. Moreover, the spin period and the range of brightness variations can provide some constraints on other important physical properties, such as density or internal structure, as has been done for other large TNOs (e.g. Jewitt & Sheppard 2002; Sheppard & Jewitt 2002; Ortiz et al. 2003, etc.)

With the goal of determining the spin period of Quaoar as well as the range of brightness variation, we performed time–resolved broad–band CCD photometry of this TNO, which is presented here.

2. Observations and data reduction

The observations were carried out using the Instituto de Astrofísica de Andalucía 1.5 m telescope at Sierra Nevada Observatory, in Granada, Spain. The data were obtained on March 4, 5, 8, 9 on May 20–23, 25 and on June, 17–22, 2003. Geometric data of Quaoar at the dates of the observations are shown in Table 1.

The March data set was acquired with a 1024×1024 fast read-out CCD camera based on a Kodak KAF-1001E CCD chip. The field of view is 7 arcmin × 7 arcmin. The exposure time used was 100 s (short enough to avoid noticeable trailing of the object under the best seeing conditions, but long enough so that the sky background was the dominating noise source). In order to get the highest possible signal to noise ratio, the observations were obtained with no filter. The typical error bars of the individual 100 s integrations were around 0.06 mag. This could be improved considerably by averaging or "median averaging" the large amount of relative photometry data points. The approach of averaging is similar to using longer integrations times, but has the advantage that no trails are present in

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Table 1. Dates and geometric data of the observations. r_h is the heliocentric distance, Δ is the geocentric distance and α is the phase angle.

r_h(AU)	Δ (AU)	α(deg)	Observing dates
43.41	43.38–43.30	1.30	4, 5, 8, 9 March 2003
43.40	42.42–42.41	0.35–0.25	20–23, 25 May 2003
43.40	42.42–42.44	0.36–0.46	17–22 June 2003

the images, cosmic ray hits are fewer and the images are also less smeared.

The May and June data sets were obtained with a different CCD camera. The CCD chip of that camera is a 2048 × 2048 Marconi-EEV CCD42_40 covering a field of view of 7.85 arcmin × 7.85 arcmin at the telescope focal plane. Most of the observations were obtained with no filter, but some data were taken in the Johnson-Kron-Cousins *BVRI* in order to make absolute calibrations possible, if needed. The exposure time used for the unfiltered images was 300 s, still short enough so that trailing was negligible. The average signal to noise ratio in apertures twice the size of the seeing disk was above 100. A fast readout A/D converter of the CCD camera was used in order not to spend large fractions of the nights reading out the CCD. In addition, the images were acquired in the binning 2 × 2 mode.

The typical seeing during the observations ranged from 1.3 arcsec to 2.5 arcsec, with median around 1.8 arcsec. The images were bias subtracted in the standard way and flat-fielded using the median of a large set of twilight images. No cosmic ray removal algorithms were used and we simply rejected the few images in which a cosmic ray hit was close to the object. Relative photometry using seven field stars was carried out by means of IDL Daophot routines based on the 1987 implementation (Stetson 1987). The synthetic aperture used was typically 8 to 12 pixels in diameter (the smallest possible in order to get the highest signal to noise). Care was taken not to introduce spurious signals of faint background stars or galaxies in the aperture. In cases where the TNO was very close to faint stars or galaxies, the data were rejected. As Quaoar moves slowly with respect to the field stars, we were able to use the same field stars within each observing run. A sample image with Quaoar and the reference field stars is shown in Fig. 1.

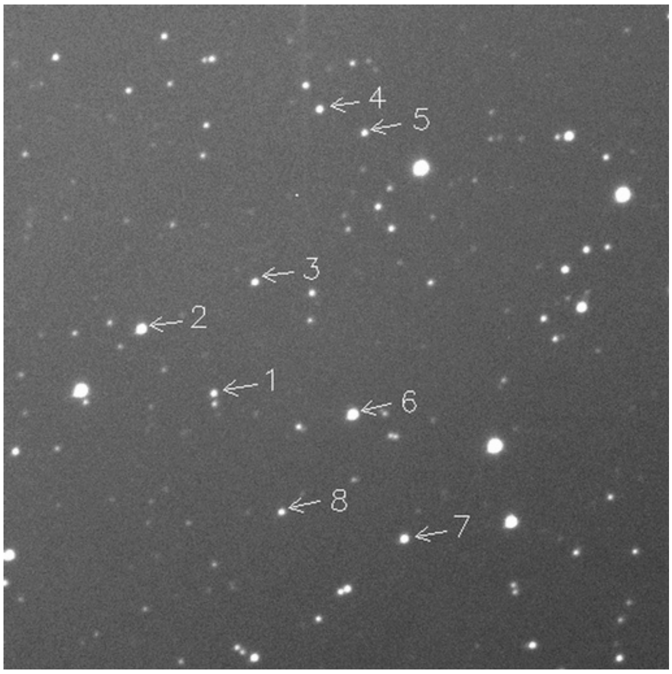

Fig. 1. A 4 arcmin × 4 arcmin window of a representative image of Quaoar taken on June 19th, 2003. The numbered arrows indicate where Quaoar was (number 1) and where the reference stars were.

3. Results

The CCD photometry of Quaoar was inspected for periodicities by means of the Lomb technique (Lomb 1976) as implemented in Press et al. (1992). The periodogram of the June data set alone (which was the largest data set, with the best time coverage), showed a main peak at 2.715 ± 0.005 cycles/day (8.84 ± 0.02 h) with a confidence level exceeding 99.9%. The confidence level was computed as explained in Gutiérrez et al. (2001). Other peaks with significantly lower spectral power were identified as aliases, at 3.71 and 1.71 cycles per day.

This period determination could be substantially improved by adding all the data sets. Prior to the Lomb analysis, the three data sets were normalized to the mean brightness of each observing run, in order to avoid possible systematic trends that might alter the periodogram analysis. The periodogram analysis of the three data sets combined (after correction for light travel time) resulted in a refined period of 8.8394 ± 0.0002 h (confidence level exceeding 99.9%). The periodogram of the combined data sets is shown in Fig. 2. The rotational phase curves from the largest data set showed evidence that the lightcurve could be double-peaked and therefore this suggested that the actual rotation period would be twice the photometric period. The lightcurves resulting from the best data sets and from the combined data sets are shown in Fig. 3.

The combined lightcurve has as many as 509 data points and we can take advantage of that in order to improve the signal to noise. Taking the median of the data in small phase bins we get the rotational phase curve shown in the upper part of Fig. 3. One of the brightness maxima is 0.03 ± 0.04 mag fainter than the other one. The peak to peak amplitude of the oscillation is 0.17 ± 0.04 mag.

Using the June data set alone, and taking the median of the data in small phase bins we find that the two maxima are different by 0.032 ± 0.028 mag, which confirms the double-peaked nature of the lightcurve. The peak to peak amplitude of the oscillation is 0.133 ± 0.028 mag. The error estimates have been made by using the standard deviation in the appropriate phase bins.

4. Discussion

The brightness changes in Quaoar are very likely due to the combined effect of rotation, irregular shape and/or albedo markings on its surface, although other possibilities exist. If Quaoar were a binary system, mutual eclipses could modulate the brightness. In this case, the brightness changes caused by

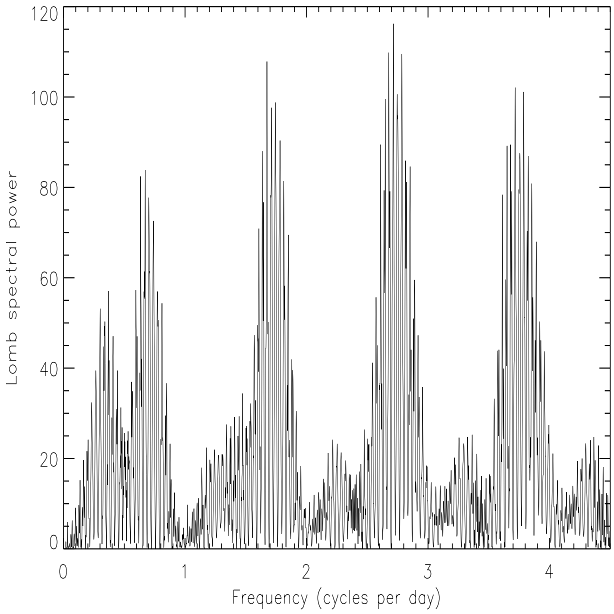

Fig. 2. Periodogram of the combined data sets.

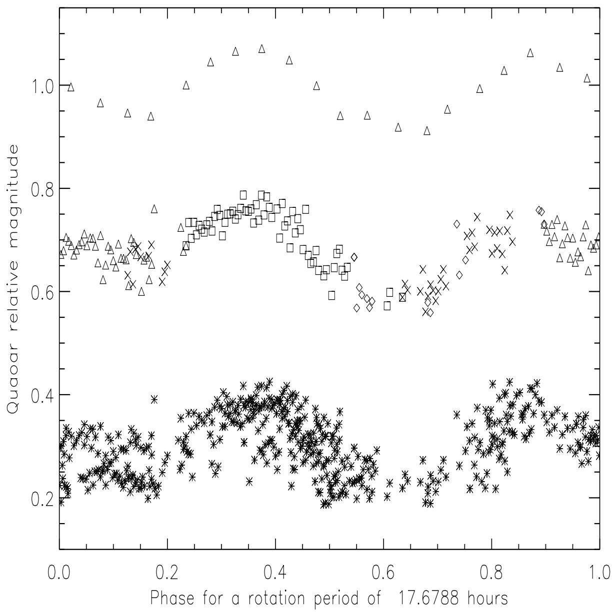

Fig. 3. Lower plot: Photometry of Quaoar in March, May and June 2003, phased to the rotation period (twice the photometric period derived from the periodogram). The phase is normalized to 1. Middle plot: photometry of Quaoar in June, phased to the rotation period. The different symbols correspond to data taken on different dates. As can be seen, there is overlap of different dates in different phase ranges. Upper plot: Rotational phase curve obtained by taking the median in phase bins of 0.05.

mutual eclipses would not be as smooth as the ones we see in Quaoar. At present, among the known KBOs (more than 600 as of this writing), less than 10 are known to be binary systems. A study by Noll et al. (2002) points out that only 4 ± 2% of the TNOs are binaries, although this number is based on the discovery of 3 binaries with a separation ≥0.15 arcsec and a *V*-band magnitude difference smaller than 1 mag, in a sample of 75 TNOs. Furthermore, Noll et al. (2002) do not rule out the possibility that their current estimate of the fraction of binary TNOs may be significantly smaller than the real one, in case faint and close-in companions are as frequent among TNOs as in the main asteroid belt. Even if the Noll et al. (2002) estimate were smaller than the actual one, it is still unlikely that Quaoar's variability is due to a binary system. A contact binary is a different issue, although this case can be viewed as an extreme case of irregular shape. If Quaoar is a contact binary, a crude lower limit to the density can be obtained from the period and lightcurve range. Using expression (6) of Jewitt & Sheppard (2002) the lower limit to the density would be 91 kg m^{-3}. This is based on the assumption of spherical shapes, identical densities and the same albedos of the two bodies

In general, double–peaked lightcurves are attributed to the rotation of an irregularly shaped body while single–peaked curves are attributed to albedo variations on the surface. Nevertheless, as demonstrated by Russell (1906), the effects of the irregular shape and albedo cannot be distinguished with a single color lightcurve. An appropriate albedo distribution can lead to a double–peaked lightcurve even for spherical bodies. So far, the only method to reliably distinguish shape–induced from albedo–induced brightness variations is simultaneous observations in the visible and in the thermal infrared. Also, time–resolved color measurements can help. Albedo–induced brightness variations are frequently accompanied by color variations along the rotation period, whereas shape–induced variations usually are not (e.g. Jewitt & Sheppard 2002). On the other hand, taking the results of other minor bodies observations into account, albedo variegations frequently produce smaller brightness changes than the shaped–induced ones. Typical short–term variability amplitudes due to albedo are smaller than 0.15 mag. We do not have time–resolved color information (the *BVRI* images that we took for calibration purposes pertain only to a very small rotational phase range) and Quaoar shows short–term variability with an amplitude which is in the order of 0.15. Therefore, we cannot reliably conclude whether the final reason for the observed brightness changes is the irregular shape, albedo variegations, or both of them. In the following, we briefly discuss some consequences of the two extreme cases.

In an in–depth study, Jewitt & Sheppard (2002) discuss about the possible causes for the variability observed in Varuna, which is also a 1000–km sized TNO. From their study, they conclude that Varuna may be a rotationally distorted rubble pile with a likely density around 1000 kg m^{-3}. In principle, this could be the case with Quaoar as well, although its spin period is significantly longer than that of Varuna. Under the assumption that the cross–section changes are responsible for the observed variability in Quaoar, the minimum axial ratio deduced from the amplitude of its lightcurve is 1.13. This minimum axial ratio would represent the actual ratio only if the aspect angle is 90°. If the aspect angle were 60°, the amplitude of the lightcurve would imply an axial ratio of 1.30.

If Quaoar is assumed to be prolate with no internal tensile strength, rotating with a period of 17.7 h, and according to the expression given by Davidsson (2001), the minimum density required to avoid spontaneous rotational breakup is 40 kg m^{-3} for the first axial ratio and 45 kg m^{-3} for the second one.

These densities are much lower than the typically expected densities for TNOs and therefore Quaoar would be mechanically stable even if it is a strengthless rubble pile. It may be worth mentioning that the relations by Davidsson (2001) were derived under the assumption of a uniform internal mass distribution. However, Quaoar is so large that gravitational compression of the core region may be of importance. This would most certainly make the body even more stable against rotational breakup.

Under the assumption of Quaoar being an irregular body, and because the deformation of the body would not be negligible, one may wonder whether the HST size measurements carried out by Brown & Trujillo (2002) could have been made at a time near the maximum of brightness or near a minimum. In those cases, the size would have been overestimated or underestimated respectively. However, by phasing our lightcurve to the date and time at which the Hubble Space Telescope images were taken, it turns out that the magnitude at that time would be just 0.02 ± 0.01 mag above the average. The uncertainty in the rotation period is small enough so that the uncertainty in the rotational phase at the time of Quaoar's measurements is less than 3 degrees and therefore the uncertainty in brightness is also small. Thus, it can be concluded that Quaoar's size estimate by Brown & Trujillo (2002) corresponds to the average size, and is not affected by any systematic bias from rotation.

On the other hand, if Quaoar were a spherical body, the photometric range of the lightcurve implies that the maximum and minimum values of the disk-integrated albedo would differ by 13%. This could be caused by the presence of a large area with slightly different albedo than the other hemisphere, or by a different configuration of bright/dark spots. If the spherical body is rotating with the spin period of 17.7 h, its minimum density to avoid rotational breakup would be 35 kg m^{-3}. This low value indicates that Quaoar is mechanically stable under rotation. Nevertheless, and also according to the equations given by Davidsson (1999), the minimum material strength necessary to withstand shear fracture and stay intact ranges from 48 kPa for a density of 100 kg m^{-3} to 482 kPa for a density of 1000 kg m^{-3}. That means that if the tensile strength of Quaoar for a particular density is lower than the needed value, then Quaoar could be internally fractured. In order to put these shear strength values into some context, it is worth to mention that the shear strength of solid ice is in the order or the MPa (e.g., Dobrovolskis 1990).

5. Summary and conclusions

As a result of an extensive photometric campaign, short–term variability in Quaoar has been detected, with a photometric period of 8.8394 ± 0.0002 h and a peak to peak amplitude of 0.133 ± 0.028 mag. The lightcurve seems to be double–peaked and therefore the most likely spin period would be 17.6788 ± 0.0004 h. For this spin period, the minimum density required to be mechanically stable is lower than 45 kg m^{-3}. As the density of Quaoar is likely larger than this limit, this TNO would be stable under rotation even if it is a strengthless rubble–pile.

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