Photometric Observations of Asteroid 2004TY16

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ABSTRACT

In this project we observed a minor planet 2004TY16 (170891) with a 1.23m CCD telescope from the Calar Alto Observatory in Andalucía, Spain. The resulting images were trimmed, reduced and used to determine the instrumental magnitude of the asteroid. These instrumental magnitudes were converted to apparent magnitudes through use of a reference star. Images were taken in Johnson V, B & R filters allowing for the colour index of the asteroid to be evaluated. The colour index was shown to remain constant at different times. Differential photometry with the same reference star lead to construction of a lightcurve for the asteroid which shows a strong agreement with a lightcurve from published literature. Analysis of the lightcurve indicates that the asteroid has a spherical shape and uneven surface. The tangential velocity of the asteroid was calculated a number of times giving a mean value of 3.87 ± 0.04km/s. The methods and results from the project were very encouraging and offer exciting opportunities for further research through photometric and/or spectroscopic observations.

Keywords: asteroid, photometry, lightcurve.

1. INTRODUCTION

Asteroids are minor planets of the inner Solar System, usually formed from shattered remnants of planetesimals or as bodies within the Sun's solar nebula which never grew large enough to become planets. Most known asteroids are located in the asteroid belt between the orbits of Mars and Jupiter, or are co-orbital with Jupiter. They are usually classified in three main groups: C-Type, M-Type, and S-Type, which are named after their carbon-rich, metallic, and silicate compositions, respectively. These three groups can be further divided into many subclasses depending on their spectral parameters. The study of asteroids is a topic of interest due to their status as remnant debris from the inner solar system formation process. Because they often are collisional fragments, asteroids give fantastic insight into processes that are hidden on the terrestrial planets by time, geochemical evolution, or simply deep burial (Britt 2020). Asteroid and meteorite impacts with Earth during its early formation have had effects on its bioshpere that still show themselves to this day.

Asteroids are typically studied through photometry. Light from the sun is reflected off asteroids towards earth at varying intensities, and it is this light that gives us most of the available information about asteroids. By using multiple filters to detect different wavelengths of light, the colour index of the asteroid can be found. Most published data says that the colour index is essentially invariant at the level of ± 0.05 magnitude (Buchheim 2010), but some more recent studies have suggested that it may change with phase angle (Belskaya, I. N. et al. 2010). The asteroid's magnitude is plotted against time to show a lightcurve. Asteroids usually produce periodic, sine-like lightcurves due to their relatively short rotational periods and spherical shapes. From these lightcurves we can obtain a vast amount of information about the asteroid, such as correlations between rotational period and size.

Constructing multiple lightcurves leads to the evaluation of the absolute magnitude (H) and slope parameter (G). Unlike stars, the absolute magnitude of an asteroid can have more than one value. This leads to the adoption of the $H-G$ magnitude system by the International Astronomical Union in 1985. This system allows comparison of the brightness of an asteroid at different apparitions, which is necessary for studies of asteroid shapes and pole positions (Dymock 2007). Once H and G are known, the visual magnitude of an asteroid can be calculated for any date.

2. OBSERVATIONS & DATA ANALYSIS

Observations took place on 11^{th} March 2022 from 01:09 to 03:32 UTC using the 1.23m Telescope at Calar Alto observatory. Weather during this period was reasonably clear, allowing high-quality images to be produced. The target for the observations was asteroid number 170891, 2004TY16. It is an Amor-type asteroid with an orbital perihelion close to, but greater than, the orbital aphelion of Earth. It is classed as a Near-Earth object.

Images were taken with a 60 second exposure time. This was just long enough to give a signal-to-noise ratio (SNR) > 100 for each image, giving a photometric error on the order of 10^{-3}. Of the 113 images taken in this period, 109 were taken in Johnson V filter. At two points during the observations a V-B-R imaging sequence was used, resulting in two images each in the B and R filters. The target is known to have a rotational period of 2.795 hrs (Carbognani 2008) so the goal of the observations was to observe at least one full period. Unfortunately the target passed out of the telescopes FOV after 136 minutes, which ended the observations. Flat and bias frames were taken later in the night and the subsequent images were reduced to correct for their effects.

2.1. *Data Analysis: Tracking the Target*

To speed up the data analysis, a function had to be written that could find the coordinates of the asteroid in each image. This was an important part of the analysis as the degree of accuracy to which the asteroids location was known would greatly affect the accuracy of photometry for each image. To implement the function, the `SourceDetect` function in `astropy` was used to locate the initial position of the asteroid in the first image. Its coordinates were used as an input parameter in the function. This function produced a list of coordinates and those suitable had to be manually selected. Once the initial coordinates were discovered the function ran `SourceDetect` again in the next image. It then searched through the list of coordinates produced and found any sources that were close to the initial coordinates. Any source within a limit of ± 10 pixels in the x-axis and ± 20 pixels in the y-axis were added to an array of potential suitable coordinates. To account for any cases where there may have been multiple sources within these limits, the function found the source whose distance from the initial coordinates was shortest and chose this as the asteroid's coordinates for that image. It then set these coordinates as the starting point for the next iteration. Once implemented, the function reduced what could have been hours of work to manually detect our target in each image into approximately 30 seconds of computing time. During the observations, the telescope had to be repositioned after 63 images had been taken to keep the target in the centre of the frame, leading to two sets of data that looked quite different from one another. The tracking function could be run for either set once the initial coordinates for each were manually selected.

2.2. *Data Analysis: Photometry*

To provide accurate aperture photometry, each image needed its ideal Full-Width Half Maximum (FWHM) and aperture size to be determined. With the set of coordinates (x_0,y_0) from our tracking function these were quite simple to calculate. An array of pixel values from $y_0 - 10 \rightarrow y_0 + 10$ along x_0 were plotted to produce a peak. This peak was fitted to a Gaussian distribution and the FWHM was found with the `SciPy sproot` function. The ideal aperture size was calculated by performing aperture photometry on the asteroid for different aperture sizes ranging from a radius of 1 pixel to 10 pixel. The SNR for each aperture radius was calculated and a plot of radius against SNR was created. The maximum SNR could then be visualised and the corresponding aperture size saved. Simple functions were created that could quickly calculate the FWHM and aperture size appropriate for each image.
The magnitudes were then determined using aperture photometry. A circular aperture was placed around the asteroid and surrounded with a circular annulus which was used to determine the background counts. The average background counts were subtracted from the flux and this was converted to instrumental magnitude through the magnitude-flux equation

$$m = -2.5 \log_{10}(F). \tag{1}$$

The error on instrumental magnitude was given by

$$\Delta m = 2.5 \log_{10}(1 + \frac{1}{SNR}). \tag{2}$$

Instrumental magnitude then had to be converted to apparent magnitudes. To do this a reference star was needed. It was tracked through all the images and its instrumental magnitude was calculated using the same method as described for the asteroid. The stars calibrated magnitude in the standard AB system was compared to our instrumental magnitude, and the difference between the two was selected as the zeropoint (ZP). The reference star had a known magnitude in V, B, r and i filters, but not in R. Using equations from Lupton (2005)[1] the r and i values could be converted to R. A ZP was calculated for every image in each filter and averaged to give a unique ZP for V, B and R filters. This offset was then applied to the instrumental magnitude for all sources in the image. Once the apparent magnitudes were calculated the colour indices of the asteroid could be evaluated.

2.2.1. *Differential Photometry*

Differential Photometry measures the relative brightness between two or more objects in an image and is the method of photometry most often used in the production of lightcurves. To do this the same reference

[1] https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php#Lupton2005

star was used. However, use of the instrumental magnitude was sufficient as we were plotting a difference in magnitude which would not be affected by the ZP. The differential magnitudes were calculated by

$$M_D = M_r - M_a, \tag{3}$$

where M_r and M_a were the instrumental magnitudes of the reference star and asteroid respectively. The error on these values were simply the numerical sum of the error on M_r and M_a. This lead to the construction of a lightcurve for 2004TY16, shown in Figure 1.

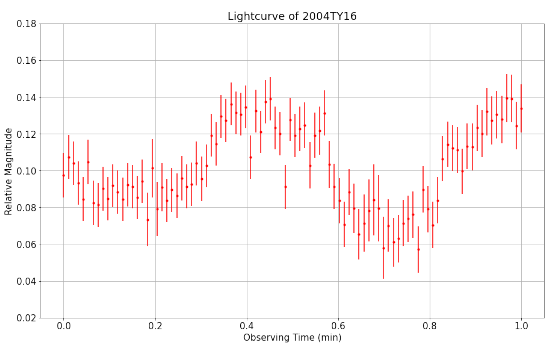

Figure 1: Lightcurve of 2004TY16 constructed from photometric observations.

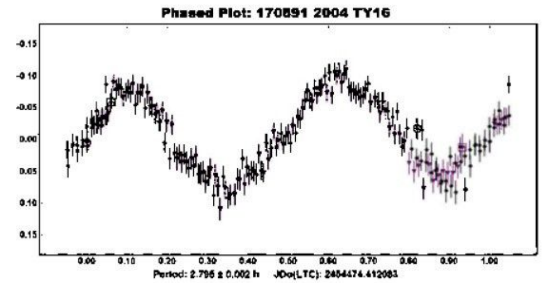

Figure 2: Lightcurve of 2004TY16 taken from Carbognani (2008).

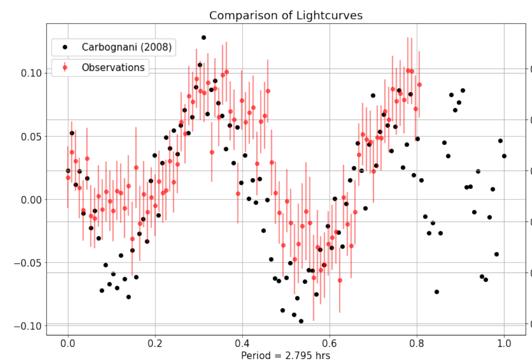

Figure 3: Overlay of Figure 1 and 2. Note the difference in how the y-axis is orientated for the data taken from Carbognani (2008).

3. RESULTS & DISCUSSION

A lightcurve of 2004TY16 was produced by Carbognani (2008) and it was converted into data points using the online tool WebPlotDigitizer by Rohatgi (2021). We see in Figure 3 that the digitized data is quite similar to that in the original image (Figure 2), aside from some messy data towards the end. It is clear upon inspection that both curves have a number of similarities. Each has 2 distinct maxima and minima. In both plots the second minimum has a greater amplitude than the first. In Figure 3 we see that the second minimum has a smaller amplitude than the first, however due to errors with the digitization and the observations ending around this time in the rotational period, it is difficult to tell how similar the curves would have been at this point. Nonetheless the three well-defined harmonics are in great agreement with one another indicating a high level of photometric accuracy in our analysis.

The variability in the lightcurve is likely to have come from its surface properties. The relatively even spacing between the harmonics indicate a fairly spherical shape. This is also supported by the fairly small changes in magnitude from minimum to maximum. Any elongation on one side of the asteroid would produce long periods of brightness, followed by a sharp decline in visible light resulting in steep, narrow minima. Assuming similar composition throughout, the two distinct minima in the lightcurve indicate an uneven surface, most likely with deep valleys or craters at these points. However without proper imaging of the asteroid at a much closer distance, any estimation of surface properties can not be confirmed. If the target had been imaged in infrared light there could have been more accurate estimations of the shape or even the size of the asteroid.

Table 1 shows the calculated colour indices for the asteroid. These values were compared to those in Tholen (1984) in an attempt to estimate the asteroid's classification. Unfortunately the values did not agree with any of the classifications in this work. The values found for the V-B and B-R indices in particular, signify a huge change in magnitude between the filters. One possible source of error may have been in the choice of reference star. The star's magnitude was almost equal to, and sometimes greater than the asteroid's magnitude. Perhaps a brighter target should have been chosen. However, the need for the reference star to be visible in both telescope positions was a massive constraint when this was chosen.

The tangential velocity was calculated four times throughout different stages of the orbit. To do this the

Table 1: Colour indices for 2004TY16 at different times throughout its orbit.

Filter 1	Magnitude 1	Filter 2	Magnitude 2	Colour Index
V	14.7 ± 0.2	B	15.77 ± 0.06	V-B=-1.1 ± 0.2
V	14.8 ± 0.2	B	15.84 ± 0.06	V-B=-1.0 ± 0.2
V	14.7 ± 0.2	R	14.50 ± 0.05	V-R=0.2 ± 0.2
V	14.8 ± 0.2	R	14.41 ± 0.05	V-R=0.5 ± 0.2
B	15.77 ± 0.06	R	14.50 ± 0.05	B-R=1.3 ± 0.1
B	15.84 ± 0.06	R	14.41 ± 0.05	B-R=1.4 ± 0.1

Table 2: Tangential Velocity

$RA_1(^\circ)$	$Dec_1(^\circ)$	$RA_2(^\circ)$	$Dec_2(^\circ)$	$\Delta t(s)$	V_t(km/s)
171.474±0.005	-14.341±0.005	171.471±0.005	-14.356±0.005	2408.632	3.74±0.04
171.471±0.005	-14.356±0.005	171.469±0.005	-14.367±0.005	1793.561	3.59±0.04
171.469±0.005	-14.367±0.005	171.467±0.005	-14.409±0.005	2080.745	4.08±0.04
171.474±0.005	-14.341±0.005	171.471±0.005	-14.396±0.005	8216.325	3.88±0.04

relevant images were analysed on nova.astrometry.net (Lang et al. 2010) to get the World Coordinate System (WCS) information. This allowed for the Right Ascension (RA) and declination (Dec) of 2004TY16 to be estimated. The Earth-object distance at the time of observations was 0.2221au (Chesley & Milani 1999). The difference in RA and Dec and the distance to the object allowed for a simple calculation of how far the object had moved using trigonometry. Knowing the time elapsed between images meant we could simply divide this distance by time to get the tangential velocity. Three of the measurements used images taken around 30 minutes apart, and the final measurement used the first and last images. These results gave an average tangential velocity of 3.87 ± 0.04km/s.

4. CONCLUSIONS

The results indicate a reasonably high level of photometric accuracy for the most part of the experiment. Although the colour indices do not comply with any known asteroid classifications, the similarities between the lightcurve created in this study and that by Carbognani (2008) are promising. The ability to accurately produce a lightcurve for an asteroid provides great opportunities to expand on the work, in particular repeating the process at different solar phase angles to evaluate the slope parameter and absolute magnitude. The tracking function proved extremely useful. Further refinements could be made to improve its speed and to add in features to account for occultations in the orbit. Nonetheless this function greatly aided the analysis and, with some adjustments, would be very useful for investigating asteroid orbits or following potentially hazardous objects.

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