Estimating the Rotational Period of 291 Alice

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The project my group selected used photometry to measure the brightness of a rotating asteroid over time and form a light-curve. Using the repetition of the light-curve, we hoped to measure the rotation period of the asteroid, a technique known as light-curve inversion. The final measured rotation period was 4.282 ± 0.20 hours, which differs from the accepted value by less than 1%.

Introduction & Background

The goal of the project was to observe the asteroid 291 Alice and use this data to generate a light-curve mapping the asteroids magnitude over time. The light-curve can be used to describe the period of the asteroid's rotation, as the shape or composition of the asteroid will cause it to have a different magnitude as its rotation causes different parts of the asteroid to face the Earth.

Light-curves are a powerful tool for learning the properties of dim and difficult to resolve asteroids. While the rotational period of the asteroid in question is the simplest property that a light-curve can describe, one could also determine other properties such as axial inclination and geometric shape. The technique of determining various properties of an asteroid based on the light-curve alone is known as light-curve inversion [1].

The study of asteroids can reveal the history of the Solar System, particularly regarding the formation of planets and moons. Asteroids are also critical for the study of astronomical chemistry and played an important role in the evolution of life on Earth [2]. They also pose a potential threat to life on Earth, which alone warrants their monitoring and study. While our project did not explore any of these characteristics of asteroids, they nonetheless prove that the subject matter is worthwhile.

Alice 291 was chosen as the target because it was visible during our observing time and acceptably bright because of its proximity to the Sun, orbiting at the inner edge of the asteroid belt with a semi-major axis of 2.2 AU [3]. The asteroid has spectral type S, meaning it is made of silicate rock that is chemically similar to the crust or mantle of Earth [2].

Observation

Weather conditions on our assigned observing night prevented us from taking the observations we used ourselves. The following week, the class instructor had to take them and send the data remotely. However, several features of the observing run still bear mentioning. The filter used for the observation was the Harris R filter [4], approximately corresponding to reddish visible and near infrared light. The transmission graph is reproduced in this paper below in Figure 1. This is ideal for the observation of asteroids, as most of their radiated light is in the near-infrared spectrum, as they radiate thermally, similar to how a stove will glow red when heated[5].

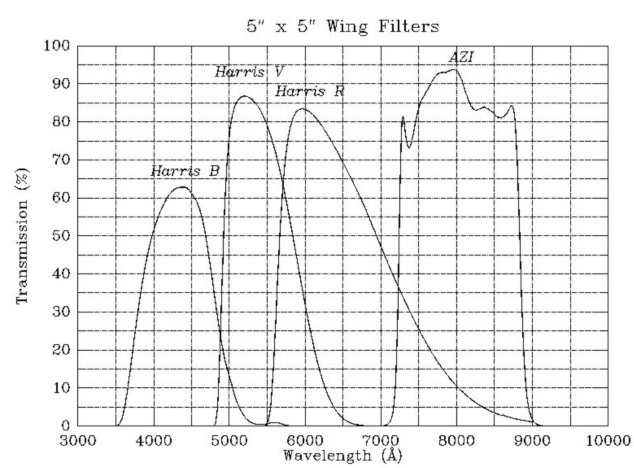

Figure 1: The different filters allow different wavelengths of light through, to allow for observation of objects that may be brighter in that band than others. The Harris-R filter allows transmission of red and near-infrared light. Image Credit:[4]

Other quirks of the observing run include a bright background because of a near full moon, and the movement of the asteroid across a bad column of pixels in the Mont4k CCD, which would later necessitate the removal of that data. The project of choice only requires accurate measurements of flux and does not require good spatial resolution. By using 3x3 pixel binning the observer increased the speed of the imaging, reduced the read noise of the CCD, and improved the photometric measurements.

Data Analysis

The bias subtraction, flat-fielding, and bad pixel correction of the images were completed during the observations, leaving only the cosmic ray removal and photometry.

When performing photometry, I have to account for the motion of the asteroid. The telescope did not move with the asteroid, and as a result the asteroid moves upwards and to the right in the image. The iraf aper command requires the location of the object. To account for the moving asteroid, I used the suggestion of the instructor and manually found the location of the asteroid in a few images and used that same location for other images soon before or after it. So I would take the location of the asteroid in image 10, and then use those coordinates for images 1 to 30. This reduced the immense workload of finding the asteroids location in 500 images while still maintaining acceptable accuracy.

The command simultaneously measured the flux of several stars in the background. Instead of graphing the magnitude of the asteroid, I want to graph the magnitude of the asteroid divided by the average of the magnitudes of each of the stars. The hope is that this will remove the contribution of the variable conditions through the night our even across the CCD, while the differing magnitude because of the asteroid's rotation will be highlighted. The resulting light-curve is produced in Figure 2 below.

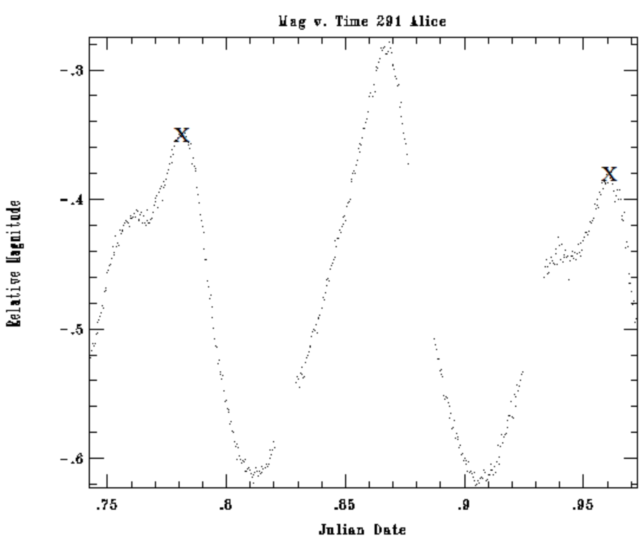

Figure 2: This is the light-curve of Alice, averaged against the magnitude of the backgrounds stars, causing the magnitude value to approach unity. The light-curve shows periodic behavior, and the X's mark the two times I used to estimate the period.

Notice the x-axis of the above curve is modified to only include the decimal values of the Julian date. The whole number of the Julian date (2458560) is the same for every date point, and trying to graph it with that date included did not work.

I also want to find some kind of error on my magnitudes, even though the error on that measurement is not directly tied to the measurement I want to make. I still want some verification that the photometry produced reasonable results. To do this I want to calculate the signal to noise ratio, given in equation form below.

$$\frac{S}{N} = \frac{gS_{targ}}{\sqrt{gS_{targ} + ngS_{sky} + ngS_{dark} + nS_{read}^2}}$$

For calculating the signal to noise ratio, we were reassured that we could ignore the sky contribution. Even though the sky was unusually bright that night on account of the full moon, 291 Alice is so bright in comparison that the contribution would still be negligible, and the only sources of noise are the readout noise and dark current in the CCD. However, I still elected to include the sky noise because I saw it was listed in the files created by the phot command, and including them was not much extra work. The gain of the Mont4k CCD and dark current were taken from an online database[4]. The read noise was taken from a header, as it was not in agreement with the value reported the previous source. I elected to trust the header's value based on the primacy of recency.

If we take the noise in the ratio to be the standard deviation of our flux measurement, then the reciprocal of the signal to noise ratio is our percent error. Because the ratio is unitless, I can use it to find the uncertainty in any brightness measurement, even though we used the counts to calculate the ratio. This is ideal because my graph used magnitudes, and converting the noise for each measurement to magnitudes requires the following equation.

$$m = ZP - 2.5log(counts)$$

This equation requires the zero-point magnitude of the image, and our headers do not include this information. After completing this analysis, I find the error bars are generally invisible on the graph. For the sake of demonstration, I included the error bar graph, but they tend to be mostly invisible in comparison to the data points themselves. This suggests the magnitude measurements are highly accurate, which is what I wanted to know. The graph is included below as Figure 3, and is also modified to only include the decimal values of the Julian date.

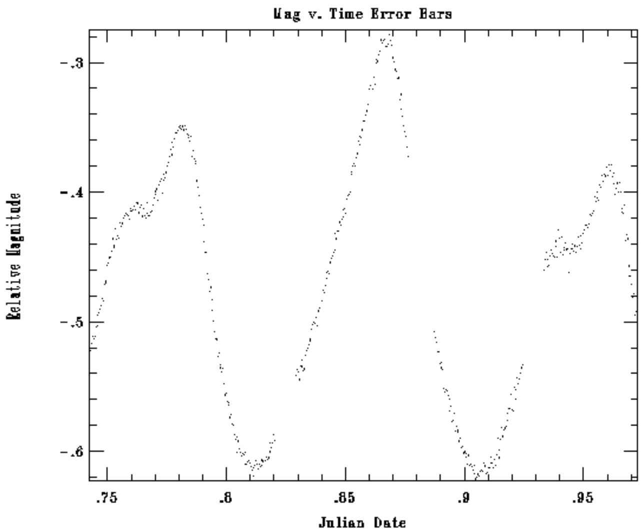

Figure 3: This shows the error bars of each point in the light-curve. The points are so small that this graph looks nearly identical to the actual magnitude graph, but close examination will reveal that some of the points are stretched vertically slightly.

Finally, I also want to mention that there are two extra "holes" in the data even after removing the bad images. These gaps correspond to the removal of a few data points that were far too dim, and obviously incorrect. The cause of these dim measurements is not known, but it seems to have been the result of an error in the phot command.

Scientific Analysis

The only measurement I want to make is the period of the asteroid's rotation. Doing this simply requires an eyeball of where the curve looks similar. I will start by assuming that the same magnitude corresponds to the same part of the asteroid facing towards us. However this gives me nearly 6 different times to compare, so I also want to look at the behavior around each point on the graph, and look for repeating behavior. It seems likely that the plateau followed by a secondary peak that repeats itself twice in the above graphs is not merely a coincidence and represents the asteroid turning back to face the Earth. By using the interactive graph in iraf, I can find the decimal values of the Julian date at the higher peaks of the light-curve feature and subtract them. The left peak is at Julian date 2458560.7817 while the right peak corresponds to Julian date 2458560.9601, so subtracting them gives me a period of 0.1784 days. This leads me to a measured rotation period of 4.282 hours.

The error is the measurement mostly originates from the imprecision in placing the cursor at the top of the peak, since that must be done by hand. To compensate for this, I will say the error in each measurement is approximately half the width in the higher peak only (so not including the width of the larger peak formed by the two smaller ones) although this is probably a rather cruel underestimation of my hand-eye coordination. Accounting for this error and propagating it through both measurements creates a final figure for the period of rotation of Alice as 4.28 +/- 0.20 hours.

There are many other ways to estimate the error. One method is simply measuring the time difference between repeating behaviors for different behaviors in the graph. Instead of just measuring the higher of the two peaks, I would measure them both and then average them together, then calculate the standard deviation of the mean. The reason I did not do this is because I only trust myself to align the cursor on the aforementioned peaks- any other point would open me up to making terrible measurements. Either I make a lot of terrible measurements or one high quality one. Considering the clumsiness of the graph tool in iraf, I elected the latter, which also gave me at least some basic understanding of what the error on each measurement is.

One other possible analysis method is a Fourier transformation of the graph to get the dominant frequency of the flux changes. In this case that frequency is the frequency of the rotation, which easily transforms into a period of rotation. The width of the dominant frequency peak would constitute the error in that case, either reported by a human measuring frequency value corresponding to the peak by hand, or by whatever algorithm was used to make the transform and measure the peak. However, the magnitude graph I obtained does not seem complicated enough to warrant such a technique, since eyeballing the graph will lead to a fairly accurate result. The observation also covers such a short timescale that I am inclined towards wariness of the result. There is some change in behavior that will manifest as either other frequency peaks or skewing the result, and the graph I have only covers slightly more than one rotational period. The Fourier transform loses accuracy with fewer data points, and I do not have a lot of data to work with.

Conclusions

Thankfully, astronomers have already studied 291 Alice, which means I can compare the value I measured with the accepted value. The JPL Small Body Database Browser reports a rotational period of 4.313 hours [5]. My value of 4.282 hours thus has 0.7% difference from the accepted value. However, the mere estimation of the period is not all that can be accomplished with light-curves. The techniques of light-curve inversion extend to the estimation of axial orientation and geometric shape as well using various algorithms. The shape of Alice has actually been predicted by one of the SAGE algorithm, as seen in Figure 4 below.

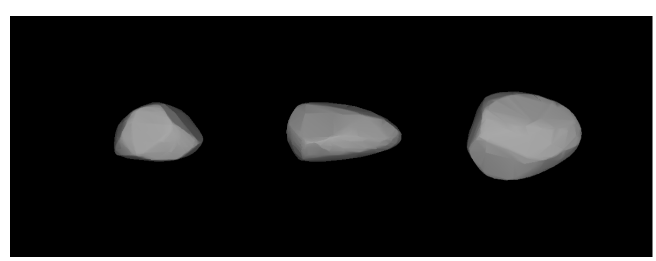

Figure 4: The SAGE algorithm predicts the shape of asteroids using their light-curve, an analysis which was performed on Alice. Reading the images left to right seems to correspond to reading the light-curve left to right starting from the left and ending at the first trough. Image Credit: [6]

This algorithm assumes the brightness changes are caused by differently sized and shaped surface areas turning towards us, and that the albedo is constant [7]. We can actually try to match the images below with the behavior exhibited in the data, with the brighter faces corresponding to troughs on our graph and the dimmer faces corresponding to peaks, since my y-axis is not inverted. The last image in the sequence definitely corresponds to the deepest trough on my plot, while the first and second images seem to represent the two sub-peaks that precede it. The larger peak, and the trough following it, don't seem to appear in the image provided.

Of course, the assumption that albedo is constant across the surface is not necessarily a good one. Not many asteroid belt objects have had their surfaces well resolved, but looking at the ones that have (Vesta, Ceres, Itokawa, to name a few) will demonstrate that there are patches of light and dark that do not seem to result from the surface's shape.

Finally, I want to briefly discuss how to build on the project in the future. Doing more light-curve inversion could be enlightening, but it has already been done, as demonstrated above. The ideal follow-up would involve taking a spectra of the asteroid, to better understand its composition. Based on the digging I have done, this measurement has not been made yet, and the finer classifications of asteroids are determined by their spectra which tell us about their chemical composition, so the observation would be worthwhile. I would have loved to do the measurement for this project, but the telescope does not have a spectrograph. Also, there may be issues with the asteroid being too dim to get accurate spectra, or the spectral emission lines being blocked by the atmosphere.

Citations

[1] "Light-curve Inversion." Light-curve Inversion, *Small Bodies Near And Far*, www.mpe.mpg.de/ tmueller/sbnaf/techniques/ a_light-curveinversion.html.

[2] "In Depth — Asteroids" *NASA Solar System Exploration*, NASA, 28 Mar. 2019, solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/in-depth/.

[3] *JPL Small-Body Database Browser*, NASA, ssd.jpl.nasa.gov/ sbdb.cgi#top.
Search 291 Alice

[4] "Operation of the Steward Observatory 61' Kuiper Telescope Mont4K D Imager.", Steward Observatory, james.as.arizona.edu/ psmith/61inch/CCD/CCDmanual.html.

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[6] "DAMIT." DAMIT – *Database of Asteroid Models from Inversion Techniques*, astro.troja.mff.cuni.cz/projects/asteroids3D/ web.php?page=project_main_page.
Search for 291 Alice, click on the first link labelled PNG. Also links to 3D model.

[7] Bartczak, P., and Dudziński, G.: 2018, *Monthly Notices of the Royal Astronomical Society* **473**, 5050.

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