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Light Curve Analysis of Asteroid 22 Kalliope

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ABSTRACT

Using the Plaskett telescope in Victoria, British Columbia, the asteroid 22 Kalliope was observed over a 5-hour period to create a light curve. A rudimentary analysis was done by matching two points on the curve with the same apparent magnitude to determine where the pattern repeats. The period obtained was 4.18 ±0.04 hours. Although this value deviates from the value measured in [1], their measurement of 4.148199 ±0.000001 hours is still within the margin of error of this observation. This discrepancy is likely the result of a less sophisticated analysis, as well as a less accurate and frequent sampling of the curve. A way to improve accuracy would be to take multiple light curves, then obtain an average curve which will be more representative of the long-term behavior of 22 Kalliope. Alternatively, the light curve inversion method outlined by [2] could also be used in tandem with long term observations to improve the accuracy of the result.

I. INTRODUCTION

22 Kalliope is a main belt asteroid discovered by J.R. Hind in 1850 with a small companion called Linus I. It has a diameter of 166.2 ±2.8 km and a mass of 7.7 ±0.4 × 1018 kg [1]. 22 Kalliope's rotational period is approximately 4.15 hours, and it's apparent magnitude is 11.4 [1, 3]. Because of its relatively high brightness and short rotational period, 22 Kalliope is an excellent candidate for light curve observations over a short observing period. The aim of this project is to find the rotational period of 22 Kalliope using a light curve. Through learning more about the rotational properties of asteroids, astronomers can gain a better understanding of their behavior and relation with other objects in the solar system. This project hopes to contribute to the long-term monitoring of asteroids and to their overall statistical picture.

II. THEORY

A. Sources of Noise

The Plaskett telescope uses a charge coupled device (CCD) to detect photons. This device converts photons to electrons which are recorded as electronic signals. These signals are processed and eventually an image can be constructed with them. When working with complex telescopes and sensors there are several significant sources of observational error.

The first issue that arises is a process called dark noise. Dark noise is the result of heat causing electrons to be thermally generated within the CCD, and these electrons are counted as a false signal. To compensate for this a dark frame is used. A dark frame is an image taken with the same exposure time and camera settings as the original science file, except with the cover left on the telescope to block external signals. This results in an image that only contains dark noise, which can later be subtracted from the original science file to eliminate this noise.

The second problem is a separate process called CCD readout noise. A CCD has an on-chip amplifier to convert the electron charge into a change in voltage. This amplifier contributes some noise during the process, which creates the CCD readout noise. To counter it, a bias frame is used, which is an image taken with the lowest possible exposure time that the camera assembly will allow. The cover is also left on the telescope to remove all signals. The resulting image only contains CCD readout noise, which can then be subtracted from the original science file to counter this noise.

The final problem involves defects along the optical assembly used for observing (including the CCD). Overtime, dust spots and other physical defects can appear on the sensor, blocking some of the signal from reaching that particular section of the view. A flat frame is taken by uniformly lighting the field of view with white light and using a normal exposure time. This isolates pixels that are covered with dust spots, as they will be dimmer than the rest. Dividing the original science file by a flat frame will normalize the pixel values, which leads to a better representation of their relative brightness without the dust spots.

An analogy for this process follows as such. Suppose there's an object 5 pixels wide, with brightness of 100, 200, 300, 200, 100. However, a dust spot covered 90% of the light for the last pixel, leading the pixel values to be 100, 200, 300, 200, 10. To correct this, a flat frame is taken with a brightness of 10, resulting in pixel values of 10, 10, 10, 10, 1(as the dust spot would continue to block 90% of the last pixel's light). After dividing each pixel by the corresponding flat values, the calibrated values of 10, 20, 30, 20, 10 were obtained. The relative size of these values is more reflective of what we would see in a measurement without the defects.

B. Light Curves

Most asteroids are not perfectly spherical and have irregular shapes. As an asteroid rotates, the amount of surface area facing Earth changes, which causes the amount of sunlight reflected to change overtime. As a result, a difference in brightness is also observed over the rotation period, and this can be measured using a light curve. A light curve is a graph displaying the amount of detected light over a period of time. For a stable rotating asteroid, plotting its apparent magnitude over time allows patterns to be discerned and its rotational period to be determined. The figure below shows a hypothetical asteroid shaped like an oblong puck as it rotates and the corresponding light curve. When more of the asteroid surface faces the observer, it appears to be brighter and a higher flux is recorded.

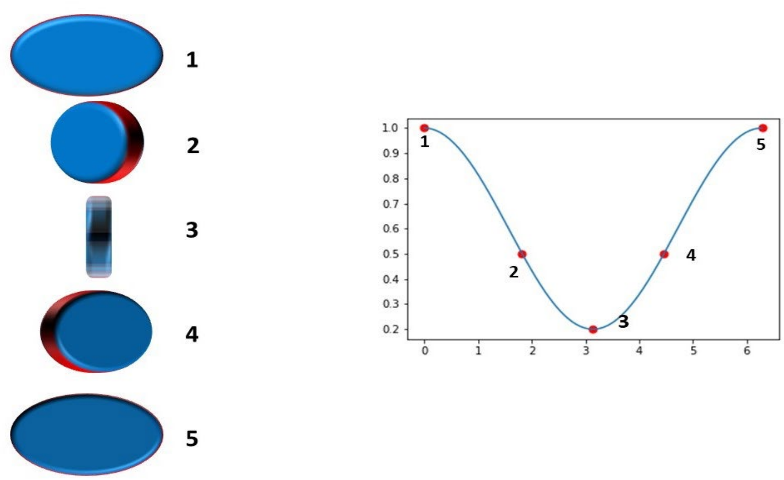

FIG. 1: A hypothetical asteroid shaped like an oblong puck rotating about its z-axis. As the object rotates, the surface area facing the observer changes periodically. The hypothetical observed light curve for this object can be seen in the plot to the right of the model.

III. DATA QUALITY

Data quality was very high. There was little to no cloud cover on the night of observation, and the only issues appearing throughout the data were meteors crossing several frames, which were all sufficiently far from the asteroid and reference stars to have no effect. Roughly 10% of frames have oblong stars resulting from inconsistencies in Plaskett's star tracking. This results in lower brightness measurements for those frames due to the inner aperture not capturing the whole area. A side-by-side picture of an uncalibrated file, and the calibrated version of that file can be seen in Figure 2. There are dark spots and black vertical lines on the uncalibrated file, which were subsequently removed by the calibration process outlined in section IV.

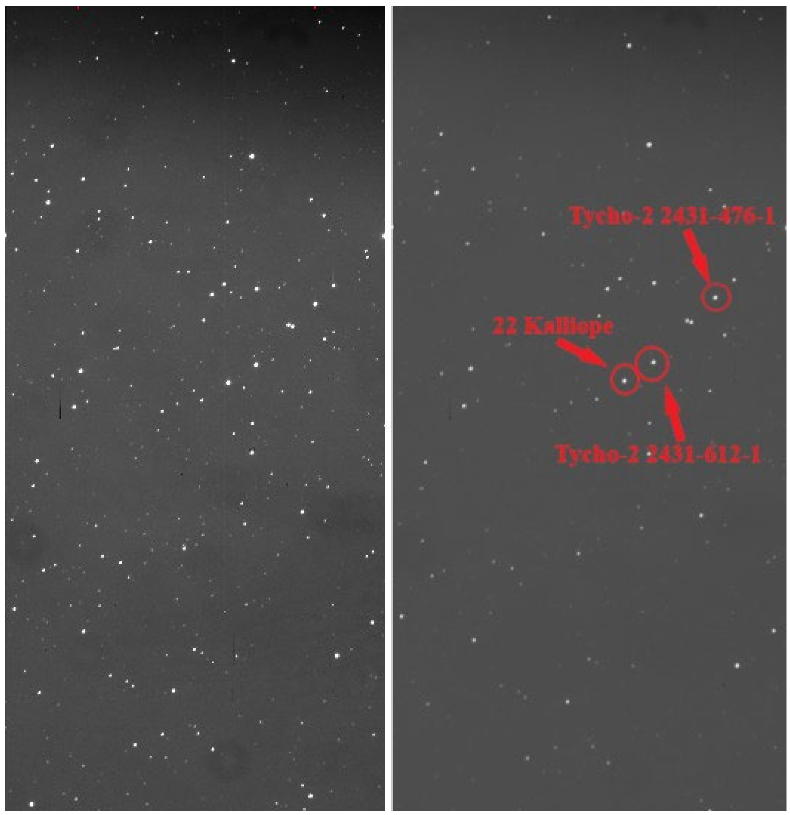

FIG. 2: A side-by-side comparison of one of the uncalibrated files (left) to a calibrated file (right). The positions of both reference stars and 22 Kalliope are indicated with red arrows.

IV. METHODS

The 1.85-meter Plaskett telescope at the Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia was used for all observations. The data was taken with a g 'filter and the CCD used is a Teledyne E2V. During a 5 hour span on the night of February 24th, 244 science files in .fits format were taken with the exposure time of 35 seconds in order to increase the signal-to-noise ratio to over 100. We were provided with 10 dark files, 16 bias files, and 16 flat files from Plaskett for calibration of the 244 science files.

A Python package called ABRIL was used to take the median of all the bias files to calculate the master bias file. The same process was used for the master dark and master flat files. The master dark and master bias files were subtracted from the original image, and the resulting files were divided by the master flat file to produce calibrated science files. Then, multi-aperture photometry was used to track the brightness of the asteroid over the 244 images in a program called AstroimageJ [4]. This method entails defining an inner and outer pixel aperture surrounding the asteroid. The inner aperture indicates the area in which the asteroid resides, and the outer aperture captures a section of sky background to subtract from the inner aperture reading. From Figure 3, it is evident that the inner aperture encapsulates 22 Kalliope's brightness and the outer aperture only contains the sky background.

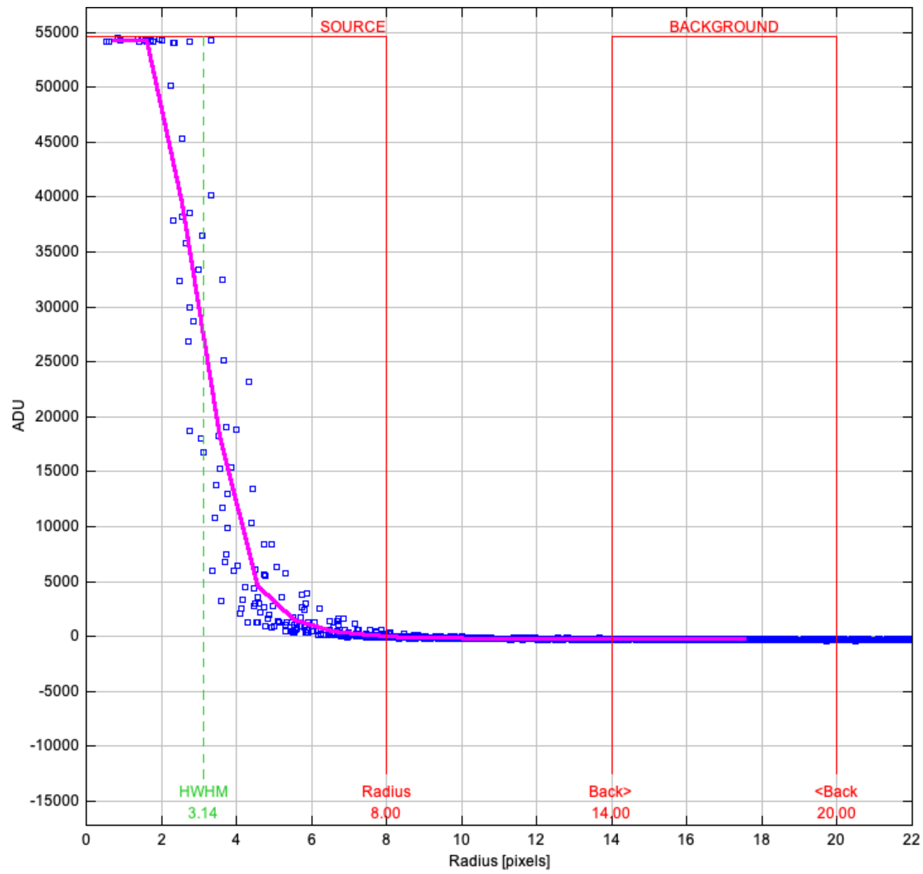

FIG. 3: A graph plotting brightness against the distance from the centre of the apertures. Nearly all the light from 22 Kalliope is contained within the inner aperture, while the outer aperture includes only the sky background.

An online program called Astrometry was used to plate-solve one of the science files, and two reference stars that appeared in all 244 science frames were detected. Star magnitudes and magnitude uncertainties were taken from Vizier [3], making it possible to convert the arbitrary system values into real fluxes and magnitudes. For the calculations, see the appendix. Once 22 Kalliope's magnitude was obtained for each image, it was plotted over the observation period to create the light curve. We then found points that correspond to the same phase in the rotation to determine the rotation period. The repetition in phase could not be determined with 100 % certainty, so upper and lower bounds were estimated to encapsulate a region where the phase repeats.

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V. RESULTS

The final light curve for 22 Kalliope can be seen in Figure 4. An estimate of 4.18 hours was initially confirmed using three points in the rotation curve that correspond to each other (Figure 5). From there the period measurement method outlined in section IV was used to obtain a rotational period of 4.18 ±0.04 hours for 22 Kalliope. The apparent magnitude of the asteroid fluctuated between 12.3 and 13 throughout the observation, and there are two large peaks in the curve separated by a 0.1 difference in magnitude. While small, the 0.1 difference in magnitude actually corresponds to a 10% change in brightness. This is large enough that the two peaks cannot be attributed to the same phase of the rotation. In fact, the second peak appears because of the deformed shape of 22 Kalliope [1]. Evidently, it has two regions with high surface area facing towards us at those points in the rotation, but they do not correspond to each other. The shape of the asteroid is complex and would require multiple sinusoidal functions to fit a curve to this light curve.

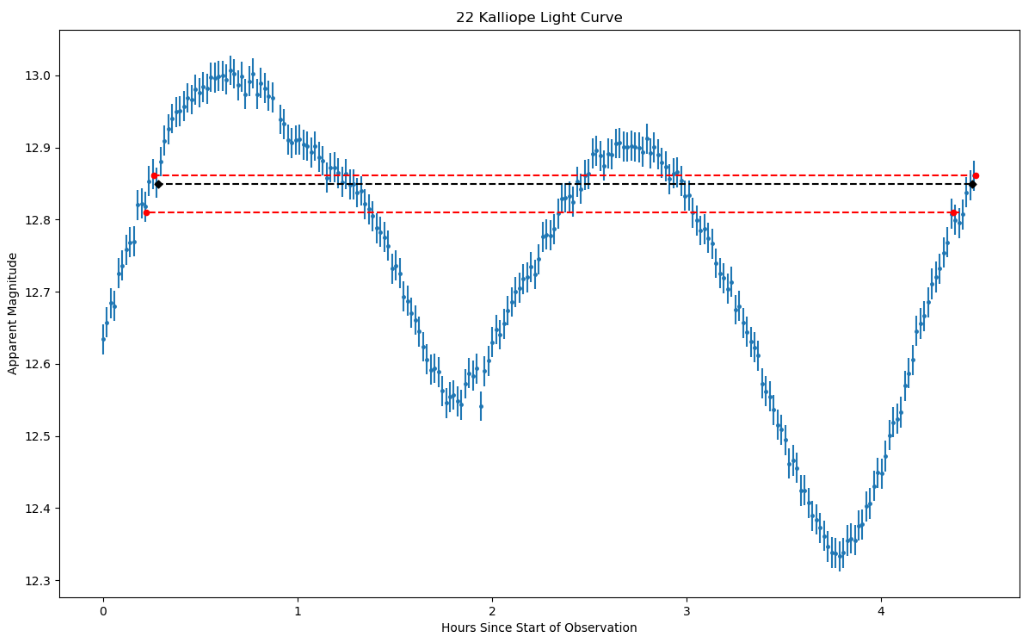

FIG. 4: The 22 Kalliope light curve with black diamonds that represent the point at which the rotational phase repeats, and red circles represent the upper and lower bounds of the uncertainty in that region. From this a rotation period of 4.18 ±0.04 hours was derived.

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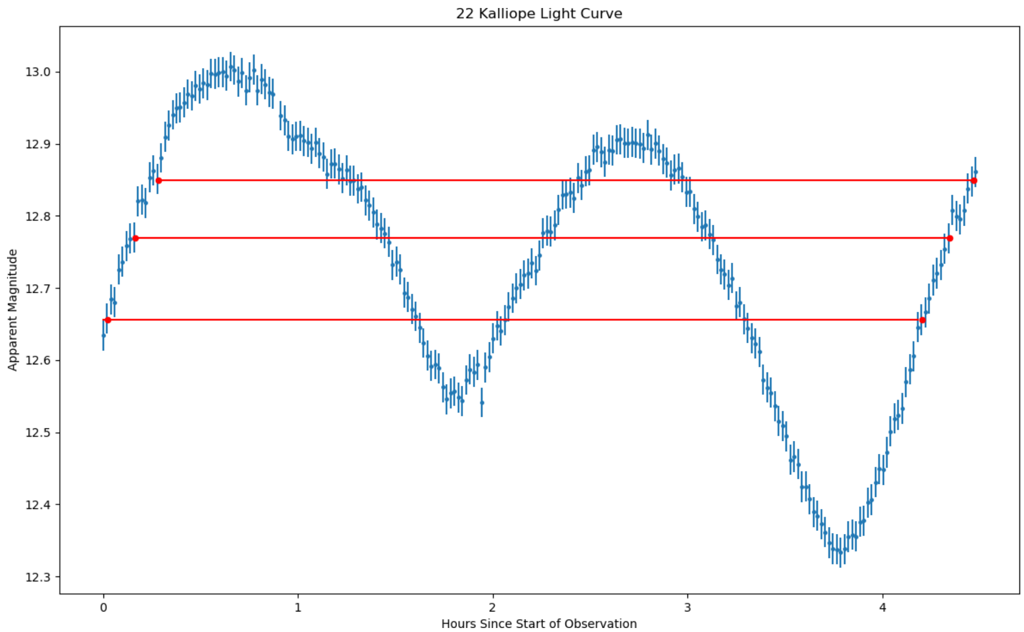

FIG. 5: 22 Kalliope light curve with red points and connecting lines showing three separate points along the curve that appear to repeat. All three returned a rotational period of approximately 4.18 hours.

VI. DISCUSSION

To better understand the accuracy of these results, the light curve was compared to [1]. There is a slight difference between the measured value of 4.18 ±0.04 hours and the value of 4.148199±0.000001 hours found by [1]. This is likely due to the distinction in methods for obtaining a rotational period. [1] used a long term observation taken by a 0.4 m telescope at the Rankin Science Observatory over a period of 4 months. A more robust method was also employed, called the light curve inversion method [2]. This method entails the use of pre-existing shape models to estimate various properties of the asteroid, including its spin period.

The highest peak to lowest magnitude distance measured here is 0.7. In comparison [1] had a curve with a difference in magnitude of 0.55 from highest peak to lowest. A comparison of the two highest peaks in Figure 4 leads to a difference of 0.1, whereas [1] has a difference of only 0.05. The differences in these values can likely be attributed to the fact that [1] has an average light curve over a 4-month period as opposed to our single observation. This long-term observation reduces noise and helps make the curve smoother. The difference between the average curve and a single observation can be seen by comparing Figure 4 to figure 1 in [1].

To improve results while still using our rudimentary method, a longer observation period would make it easier to see two points on the curve that repeat. The sampling problem could be fixed by conducting observations on multiple nights and finding an average light curve for 22 Kalliope. While these improvements would bring us closer to the actual value, it is evident that a more quantitative method (such as light curve inversion) is required to get precise and accurate spin periods for asteroids.

VII. CONCLUSION

In summary, data taken by the 1.8-meter Plaskett telescope in Victoria, BC was used to obtain a light curve for the asteroid 22 Kalliope. A simple analysis of the light curve revealed a period of 4.18 ±0.04 hours. Given the range of uncertainty, the more accurate value measured by [1] lies within our range of potential periods. This is primarily due to a less sophisticated analysis method, which still yielded an acceptable estimation of the rotation period.

Going forward, an improved value could be obtained with Plaskett by acquiring an average light curve over several nights of observing. With more time and resources, it may also be possibly to fit a composition of sine and cosine curves to the light curve in order to obtain a better period measurement. Alternatively, the light curve inversion method [2] could be used, but this would require months of observation.

While this project may be small on its own, it contributes towards our understanding of the asteroids in the solar system. Studying asteroids is important as they have abundant resources but could also be a potential threat towards life on Earth. Hopefully this project can inspire other young students to carry out similar projects with publicly available data to further our understanding of the solar system and ultimately the universe.

VIII. REFERENCES

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