Generating Variable Lightcurves of Asteroid 135 Hertha Using Differential Photometry

Alicia G. Wadsworth, Christine E. Colson, Dwight P. Russell, Dick Campbell

***Abstract*— The light that is reflected off of the surface of an asteroid varies due to a number of factors, most of which are time-dependent. It is possible to record this variation of light and subsequently analyze it to determine some of the physical characteristics of the asteroid. The researchers' eventual goal is to collect enough lightcurves from a variety of observing geometries that the lightcurves could be inverted, and a three dimensional rendering of the asteroid could be generated. This research focuses specifically on the capture and analysis of the lightcurve of 135 Hertha. Three lightcurves were gathered of 135 Hertha, two of which were considered to be acceptable in that there was little noise in the data. These two lightcurves have been uploaded to the Minor Planet Center's lightcurve database, along with one that was collected of 51 Nemausa, with the hopes that other astronomers will find them to be useful in their research.**

***Index Terms*—135 Hertha, asteroid lightcurves, lightcurve inversion**

I. INTRODUCTION

THE researchers worked over a period of roughly two months to begin to gather data. A total of 4 asteroid lightcurves have been gathered thus far. Of those, three were considered to have an acceptable signal to noise ratio, and the two of the same asteroid (135 Hertha) were chosen as the most promising for use in a later attempt at inversion. These lightcurves were gathered two days apart at the Paul and Jane Meyer Observatory using a 24" Ritchey-Chrétien telescope.

The first acceptable lightcurve of Hertha was recorded on July 14, 2015 at 04:13 (UTC), using a sequence of 20 second exposures. The second was recorded on July 16, 2015 at (03:43) UTC, using a sequence of shorter 10 second exposures to address CCD chip saturation issues that had previously arisen. The data gathered on the two days were analyzed using AstroImageJ. The images were calibrated and noise was subtracted out using the Data Processing module, and the light curve was generated with the multi-aperture photometry function. For each night, three different comparator stars were chosen to determine the relative flux of the asteroid. The data from both days, as well as the data from the previous observation of 51 Nemausa, were submitted to and are available on the Minor Planet Center's lightcurve database.

In order to attempt perform lightcurve inversion, an asteroid must be observed at multiple phase angles, as well as with multiple observational geometries. The specifics of these requirements are further discussed in the Conclusions section of this paper.

II. THEORY

Light originating from the sun is reflected off of asteroids. This light is reflected back to earth at varying intensities. The observed magnitude of the reflected light varies with the sizes of the planes that compose the surface and with the angles of the normals of those planes relative to both the sun and the earth. These angles will change with the rotation of the asteroid about its axis or axes. The observed magnitude of this light will therefore change with time, and can be recorded via Charge-Coupled Device (CCD) chip. The change in magnitude of the target object is compared with that of surrounding stars. A lightcurve is the graphic representation of this change in magnitude. If enough data were to be gathered through repeated observations and analysis, it would be possible to determine information about the asteroid, such as its rotational period, and even eventually, a rough estimate of its three dimensional shape.

LCInvert is a program based on the algorithms and code of Mikko Kaasalainen and Josef Durech, and is written to guide the user through the process of formatting the lightcurve data and subsequently inverting it [1]. The program is then capable of rendering a three dimensional model of the asteroid based on the data. The validity of the model is then estimated based on a number of parameters (see: Conclusions).

III. METHOD

For each night of observation, the researchers were careful to take data that would have a strong signal to noise ratio (around 196:1 for the first night and 147:1 for the second) without risking the saturation of the CCD chip. The focus of the telescope was adjusted until the FWMH of the target was between 3-4 arcseconds. Since the target asteroid was rather

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Manuscript received August 6, 2015. This work was supported by the National Science Foundation Grant # PHY-1262031

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low in the sky at the time of calibration (azimuth of approximately 20^0), the image was less focused that originally desired, yet still within an acceptable range.

For each night, a set of calibration images were taken prior to the observation of the target asteroid, including thirty bias frames, thirty dark frames using ten second exposures, thirty dark frames using an exposure matching that for the observation of the asteroid, and thirty flat frames using a ten second exposure. These calibration images were necessary to record and later eliminate noise that is inherent in data collection using this particular telescope and CCD chip. The biases frames, which do not require an extended exposure time, recorded the electronic noise in the CCD chip. The dark frames recorded the thermal noise in the system, and the flat frames recorded the sensitivity of the pixels in the chip. These frames were later combined and averaged into master biases, master flats, and master flats for each night, and subsequently subtracted from the science images of the target asteroid.

The telescope was then directed toward the predicted location of the asteroid using the right ascension and declination. A BG40 filter was used for the gathering of the science images. The STScI Digitized Sky Survey website [2]was used to generate the expected star field at a particular right ascension and declination. The observed star field was then compared to the generated star field, and the asteroid was located. The asteroid will not be present in the generated image, and will be visible in the telescope's field of view, which helps us to locate it. The telescope was then set to track the star field at a rate that roughly matches that of the star field. An aperture was placed on a randomly selected star so that tracking rates could be monitored and adjusted accordingly. Minute manual adjustments to the tracking rates were necessary at several times throughout each night of observation.

The images were then analyzed using AstroImageJ, a free program for editing and analyzing astronomy images. Using the Data Processing module, the calibration files were averaged to create four master calibration files. These master files were then subtracted from each of the science images of the target asteroid. This eliminated much of the error due to noise inherent to the telescope, filters, and CCD chip. What remained was then analyzed using the multi-aperture photometry function in AstroImageJ. The multi-aperture photometry function compares the selected target object (in this case, the asteroid Hertha) with several other stars that are visible in the star field. These comparator stars are selected by the researcher, keeping in mind that each must be visible for the duration of the observation time. The light curves of the comparator stars are used to correct for overall sky effects. The remaining variation of the object is the result of these corrections, since the change in intensity of light from the target object is graphed with respect to those comparators. The result is a graph of the lightcurve of the target star.

After the lightcurve was produced, adjustments were made to the scale and placement of the lightcurves of the target object and its comparators. The purpose of these adjustments was to reduce the visuals effect of noise in the data, and to generate an image that accurately depicts a smoother and more easily interpreted graph of the target object's relative magnitude over time. When the graph looked acceptable, the data table was exported to Excel, for use in further analyses in Mathematica, Matlab, and/or LCInvert. In addition, the data has been converted to fit The Asteroid Lightcurve Data Exchange Format (ALCDEF) Standard so that it may be used by other researchers.

IV. RESULTS

The researchers gathered a total of four lightcurves during this portion of the research. Of these, two were considered to be ideal to continue to work with in the future. Both are the recorded lightcurves of 135 Hertha, taken two days apart. All observations were performed at the Paul and Jane Meyer Observatory (Longitude: -97:40:27, Latitude: +31:40:52), in Coryell County, TX.

The first night of data was taken on the evening of July 14th, 2015. Observation of Hertha was begun 04:13 July 14th, 2015 (UTC). The initial right ascension of the asteroid was predicted to be 19 21 43.27. The initial declination was predicted to be -25 58 04.0. The telescope was pointed in this direction, and a single image was taken. The star field in this image was then compared to the one that had been produced by the STScI website [2], and the asteroid was located within the star field. The telescope was then set to take continuous twenty second exposures of the asteroid, and to track the star field across the sky. The protective dome was told to automatically follow the telescope as it tracked across the sky.

The telescope and images were monitored through the night, and tracking rates were adjusted as necessary. At approximately 07:45 UTC, it was noticed that the dome had failed to follow the telescope, and the dome had to be sent to home position and then retold to follow the telescope. At approximately 09:25 UTC, the dome again failed to track the telescope. At this time, it was decided to terminate observation for the night. During both times of dome failure, the telescope took several images of the inside of the dome. These files were discarded during data analysis, and the first such failure shows up in the lightcurve as a gap in the data (see: Fig. 1).

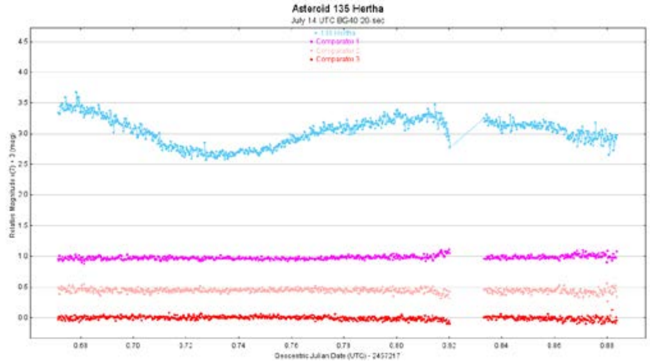

Fig. 1. The Observed Lightcurve of 135 Hertha on July 14, 2015. The figure shows the change in the observed magnitude over time, as compared with three relatively stable stars in the same star field at the same time. The gap in the data is due to the interference of the external dome for that period of time.

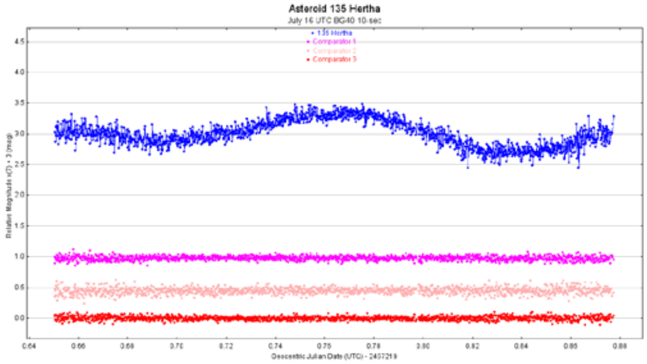

Fig. 2. The Observed Lightcurve of 135 Hertha on July 16, 2015. The figure shows the change in the observed magnitude over time, as compared with three relatively stable stars in the same star field at the same time. These comparator stars are different than those used on July 14, since the asteroid was located in a different star field.

The second lightcurve (see: Fig. 2) was also that of Hertha. Observation began at 03:43 July 16th, 2015 (UTC). The initial right ascension was predicted to be 19 19 45.73, and the declination to be -25 59 24.8. Ten second exposures were used for this observation. Tracking rates were monitored, and no major problems occurred during this run. Observation was concluded at approximately 09:00 UTC.

The two lightcurves were graphed together, maintaining the time difference. In addition, offsets in magnitude due to the difference in comparator stars and conditions of observation can be seen (see: Fig. 3). Fig. 4 shows these same curves, but with the magnitudes adjusted so as to be compared with each other.

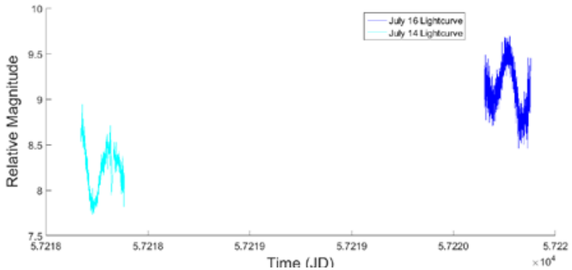

Fig. 3. Lightcurves from July 14th and 16th. The change in time between observations can be seen here, as well as the change in magnitude that results from using different comparator stars for each curve, among other things.

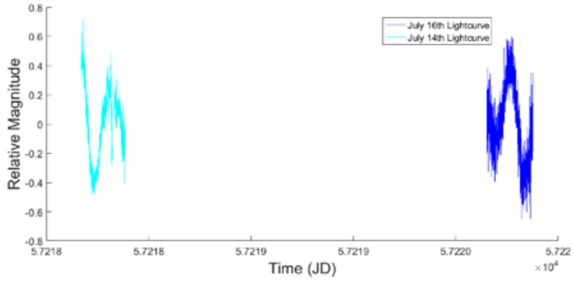

Fig. 4. Lightcurves with Adjusted Magnitudes. This data has been altered by removing the DC offset from each lightcurve.

Finally, Fig. 5 shows these curves after the time difference has been calculated. The published period of this asteroid (8.403 hours: [3]) was used to determine the time offset between observation times between lightcurves. Subtracting off an integer multiple of the period allows us to overlap the two lightcurves. The researchers believe that Fig. 5. is nearly the entire lightcurve of the asteroid 135 Hertha, missing only roughly an hour of observations.

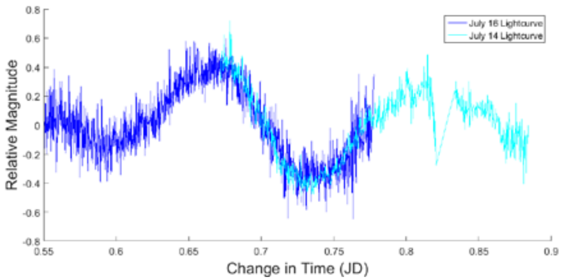

Fig. 5. July 14th and 16th Combined Lightcurve. The time differences were subtracted from the data to create what is believed to be a roughly 7.5 hour portion of Hertha’s 8.403 hour lightcurve.

V. CONCLUSIONS

Further work is required in order to reach the researcher’s goals. Many more lightcurves of Hertha must be gathered before attempting to use lightcurve inversion to generate a three dimensional model of the asteroid.

These lightcurves must be gathered from multiple viewing geometries, and with a variety of phase angles [4]. Observations of asteroids with phase angles of greater than 10^0 are often more informative than those with smaller phase angles. This is due to the extra information that can be gathered due to shadowing effects. Similarly, phase angles of greater than 20^0 are also highly informative. It is recommended that the researcher gather several lightcurves at these phase angles, and others [4]. The researchers have estimated that it would take roughly six months of observations to gather enough lightcurves of these viewing geometries.

In addition, lightcurves that are excessively sparse or noisy should be removed from the data set [4]. These can introduce biases and inaccuracies to the model, and though it is possible to weight these lightcurves so they are less significant, it is difficult and not recommended [4]. Similarly, lightcurves that contain redundant data, such as those that are very similar and were taken on similar dates, should not be included in the data.

After several solutions have been generated, the validity of these solutions must be evaluated, using the following standards: the solution must stand out from the set of many trials, it must fit (most) data to noise level, and the longest axis should not be the axis of rotation. In addition, if the ChiSq values of all solutions are very similar, it is likely that the available data may not be capable of generating a good model [4]. The LCInvert program can also be used to find the period of the asteroid, and to determine other physical features of the asteroid such as axis of rotation, semi-major and semi-minor axis, etc. The researchers intend on continuing their work on asteroid light curve inversion. Assuming their results are similar to others in literature on the asteroid 135 Hertha, they then intend to expand their efforts to beginning to study asteroids with less well-known physical characteristics.

ACKNOWLEDGMENT

This work supported by the National Science Foundation's Research Experience for Undergraduates Program, grant number PHY-1262031. A. G. Wadsworth thanks CTAS (Central Texas Astronomical Society) for the use of the Turner Research Station and the assistance of the members, as well as Dr. Dwight Russell and Professor Dick Campbell for everything they have done to help move this research forward, Willie Strickland for his assistance with the telescope and with lightcurve generation, and Drs. Truell Hyde and Lorin Matthews of Baylor University for working so hard to continue to make this program possible.

REFERENCES

[1] "MPO LCInvert." [Online]. Available: http://www.minorplanetobserver.com/MPOSoftware/MPOLCInvert.htm. [Accessed: 12-Jun-2015].

[2] "The STScI Digitized Sky Survey." [Online]. Available: http://stdatu.stsci.edu/cgi-bin/dss_form?target=lydia&resolver=SIMBAD. [Accessed: 03-Aug-2015].

[3] "HORIZONS Web-Interface." [Online]. Available: http://ssd.jpl.nasa.gov/horizons.cgi#results. [Accessed: 03-Aug-2015].

[4] "Initial Efforts at Asteroid Lightcurve Inversion - ResearchGate." [Online]. Available: http://www.researchgate.net/publication/234513017_Initial_Efforts_at_Asteroid_Lightcurve_Inversion. [Accessed: 03-Aug-2015].

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