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An Exposition on Globular Clusters: Theory and Observation

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Conference Strand: *Advancing Diversity, Equity, Inclusion, Access & Social Justice*

Abstract.
In this paper, we discuss the collaboration and focus between the Geneva Lake Astrophysics and STEAM (GLAS) group and the West Africa Office of Astronomy for Development (WAROAD). In particular, this collaboration aims to provide upcoming scientists with data analysis tools and resources in astrophysics to observe, reduce, and analyze globular cluster data from the Stone Edge Observatory (SEO). Within our framework, each student is equipped to stack images using Jupyter notebooks, plot histograms, and statistics (mean, std), observe and download images using SEO, as well as leverage different filters for mosaicing, flux calibration, and data reduction (bias, darks, flats). We show some of our initial results. In particular, we present the mosaics of our chosen globular cluster (M3), our data reduction process, and statistics of our data, as well as our work on what we have done on asteroid photometry. We also include preliminary color-magnitude diagram (CMD) of our globular cluster.

1. Introduction

With a growing demand for international collaboration among scientists in modern-day research to collectively answer questions about our universe, GLAS Education and Stone Edge Observatory (SEO) partnered with the WAROAD to create an intensive educational experience for astronomy teaching and public engagement. We leverage globular cluster (GC) studies as the perfect combination of entry-level astronomy and potential for discovery. GCs are among the most studied objects in our Milky Way and GC research has contributed to our understanding of the distribution and properties of dark matter (Bar et al. 2022), as well as what dynamic history their host galaxy underwent(Dolfi et al. 2022). However, this is still a very active area of research.

The opportunity for introductory research that also presents the possibility of discovery is a valuable experience for students. This collaboration was able to utilize SEO to study GCs such as M3. The meetings provided students with the chance to hone their data analysis skills in Astronomy using tools such as Jupyter Notebooks (Kluyver et al. 2016), Source Extractor (Bertin & Arnouts 1996), Github, SAO Ds9 (Smithsonian Astrophysical Observatory 2000), MPO Canopus (Warner et al. 2009a) among other frequently used astronomy software. These meetings and instruction provide valuable experience and resources to students, including access to the SEO telescope and its data as well as data from the Yerkes telescopes. Throughout this paper, we will discuss the structure of the program, background information, and the results of the collaboration to date. We also comment on future plans to characterize the GC properties (ages, metallicities, and colors) of the stellar populations in our clusters.

Our project involved meeting online via Zoom, utilizing Slack to communicate and observe remotely, and performing analyses online using Jupyter notebooks / online tutorials on archival and current data from the SEO telescope. This framework encourages and supports cross-cultural collaboration.

Section 2 describes the international collaboration between GLAS and WAROAD. The data collection and analysis process can be found in Section 3 for the two study cases presented in this work. We discuss the results of our data analysis in Section 4, with concluding statements in Section 5.

2. GLAS Education and International Collaboration

Geneva Lake Astrophysics and STEAM (GLAS) Education is a non-profit organization in southern Wisconsin. It was established to promote education and student research programs from the University of Chicago's Yerkes Observatory when it closed in 2018. Over the past three years, GLAS Education has lived up to its mission statement by staying committed to a mission of service, to provide inclusive STEM experiences for individual, local and global good, through innovative educational programs that are anchored in a multi-generational community and make the world a better place, through unprecedented engagement in astronomy and STEM.[1]

GLAS collaborates with Stone Edge Observatory, the Western and Southern Africa Regional Office of Astronomy for Development (WAROAD and SAROAD) to provide research experiences to undergraduate and graduate students. This collaboration was

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[1] `https://www.glaseducation.org/`

strengthened by the emergence of the COVID-19 pandemic. The need for remote collaborations has birthed a set of new students who are passionate about astronomy and space sciences. With the aid of the SEO 0.5m telescope, students are able to carry out observations from anywhere around the world. This has resulted to some publications to the minor planet bulletin (Sani et al. 2021a) and ASP conference proceedings papers(Njoku-Achu et al. 2021).

2.1. Collaboration Goals and Framework

The purpose of this collaboration is to provide a model of ongoing mentorship that can lead to published work and research skill development. Through this, we apply for grants to provide access to technology and stable internet connections, forming a nested mentorship structure that provides upcoming scientists, who have interest in Astronomy, with the opportunity to learn and develop the capacity required to identify potential targets of interest and plan observations independently. These include students at a different academic level, industry, and gender. We have targeted three sustainable development goals, which include: education, gender equality, and inequality.

- **Education:** We aim to increase scientific and research literacy, including data acquisition and analysis skills that are heavily used in present-day astronomy research. Our focus is on skills which are not only beneficial in the context academia, but are transferable to data analysis in industry. This includes a working knowledge of programming languages, including Python, as well as statistical analyses.

- **Gender Equality:** Acutely aware of the challenges associated with the participation of women in data science astronomy, we bid for an equal future and a sustainable world by integrating female leaders into the project to improve on their output in coding, data analysis, astronomy and research. The current representation of women in stem research fields in Nigeria is currently between 17 and 20 percent according to counts from 2015-18 (Ekine & Aremu).

- **Inequality:** The SEAS project has brought people together globally without any physical interaction in this era of a global pandemic. With fast, reliable and stable internet access, students and leaders can keep in touch in real-time to address problems of mutual concern without limitations of distance, time zones and climate.

2.2. Working Groups

As a stepping stone toward these goals, for this work, we focus on two science cases using photometric data from SEO and legacy data from the Yerkes Observatory telescopes: (1) the creation of a color-magnitude diagram for a globular cluster and; (2) the analysis of asteroid lightcurves. These two analyses require deep understanding of the instruments and data of SEO, and develop the computing and coding skill of the students in the program, as they use and develop software for each of these analyses.

At the end of this project, we expect these students will share the knowledge gained with their peers, schools, workplace, and country.

3. Data & Methods

As mentioned earlier, in this work we present two different study cases: Globular cluster observations, and Asteroid observations. These explore different types of astronomical objects and analysis techniques (static versus transient science), that give the students an overview of the breadth of analyses in modern astronomy.

Through these projects, students further developed their data analysis techniques and bettered their understanding of these astronomical objects. In the context of both projects, students gained programming and statistical analysis skills. Specifically, students use Python (a programming language that is extensively used in astronomy research, as well as industry) to create analysis scripts. These skills will serve them in their careers and ongoing research in the astronomical community.

3.1. Globular Cluster Observations

Globular clusters (GCs) are stable, symmetrical, tightly bound by gravity, groups of tens of thousands to millions of stars formed about 13 to 15 billion years ago, and as such they are the oldest surviving stellar subsystems in galaxies. The Milky Way Galaxy contains more than 150 GCs (Harris 1996).

A typical GC has the highest concentration of stars near its own center. In these central regions of the cluster, the stars are so closely packed that often it becomes difficult to distinguish individual light-sources from each other, whereas on the outskirts of GCs the stars are easier to distinguish. This is illustrated in Figure 1, which shows M3 (NGC 5272) in the northern constellation of Canes Venatici. The star density in the center of the cluster is much higher by measuring photometrically, which can also be seen by visual analysis.

The study of the properties of GCs in our Galaxy and in external galaxies can provide important clues on the formation and the evolution of individual globular clusters and of their host galaxies (Vesperini 2000).

GCs are of interest because they can help trace the chemical and dynamical evolution of the Milky Way. Additionally, since the orbits of GCs may have kept their characteristics from the early times of the formation of the Milky Way, we may extract from their kinematics some clues for the understanding of the origin of the Milky Way.

A basic tool in astronomy, widely used for the study of GCs is the Hertzsprung-Russell (HR) diagram. An H-R diagram, also known as color-magnitude diagram (CMD), shows the relationship between a star's temperature and its luminosity.

The need to profile characteristics of stellar evolution, in order to deduce the properties of the halo of the Galaxy, and to establish a lower limit of the age for the Galaxy and the universe has long been the driving force towards color-magnitude diagram studies of globular clusters (Peterson 1986).

In order to build the color-magnitude diagram, we need to process and measure photometric properties for objects in the globular cluster fields. Measurements of individual objects in crowded environments are particularly challenging, as overlaps between different sources are common, potentially biasing the results. Fortunately, the color determination members of the globular clusters is typically unbiased, as most of the members showcase similar colors. We collected legacy images from the SBIG STL-

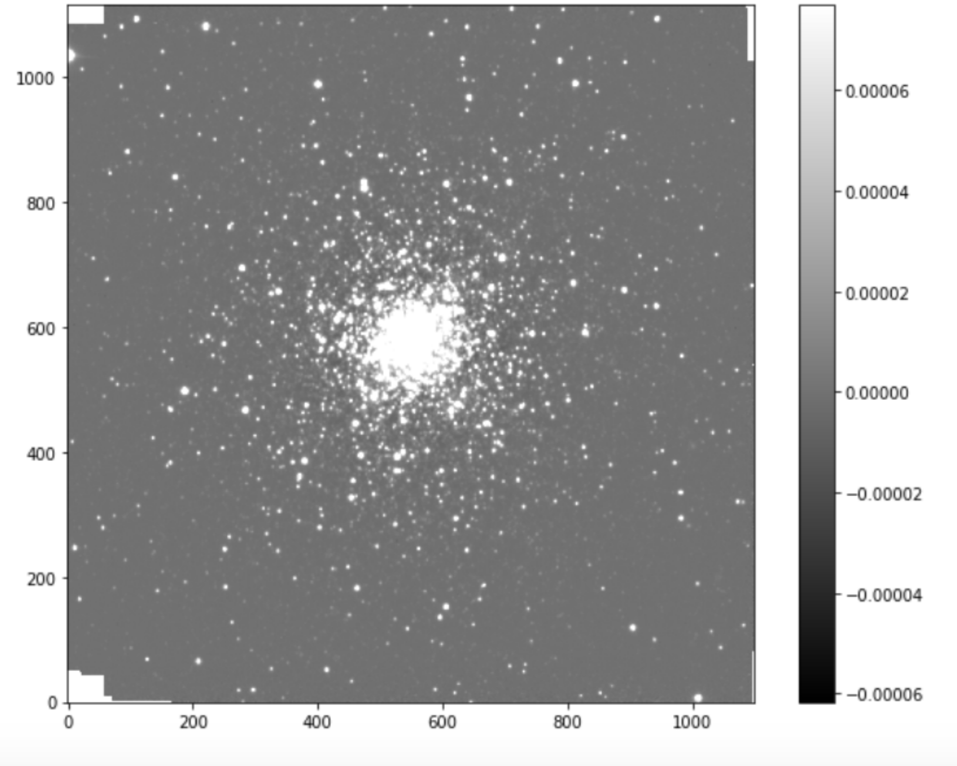

Figure 1. Background subtracted M3 Mosaic image in *r*-band.

1001 CCD[2] mounted on the Yerkes 24-inch telescope. Additionally, we supplemented images taken by the SEO camera, which uses an e2v CCD 230-42 sensor, mounted on the 0.5-m SEO telescope.[3] Each image covers a $26' \times 26'$ field of view, and are stored in FITS format. The first step in our process is to calibrate the raw images obtained by the sensor.

Following common procedure for most astronomical analyses the images are bias, flat, and dark-corrected. This calibration is carried out using a calibration pipeline specifically developed for SEO. After the image calibration, we align and coadd using inverse variance weighting the individual images of a given field in each band analyzed. We perform detection, deblending and flux measurements in the coadded images using `SEP` (Barbary 2016; Bertin & Arnouts 1996). For our studies we focus on photometric measurement using the Sloan Digital Sky Survey (SDSS) g', i' filter bands (Abazajian et al. 2009). Their throughput as provided by `speclite`[4] is depicted in Figure 2. The flux calibration is automatically carried out by the SEO pipeline by spatially matching

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[2] Technical specifications can be found at `http://www.company7.com/library/sbig/pdffiles/cat_stl.pdf`.

[3] `https://stoneedgeobservatory.com`

[4] `speclite.readthedocs.io`

with SDSS photometric catalogs and relying on the fact that our images use the same filter system. This photometric calibration procedure ignores differences in the sensor, and overall photometric throughput between the optical systems of Yerkes, SEO, and SDSS. However the accuracy of the procedure is sufficient for the purposes of this work. A detailed analysis of the flux calibration procedure is out of the scope of this work, and is open for future studies.

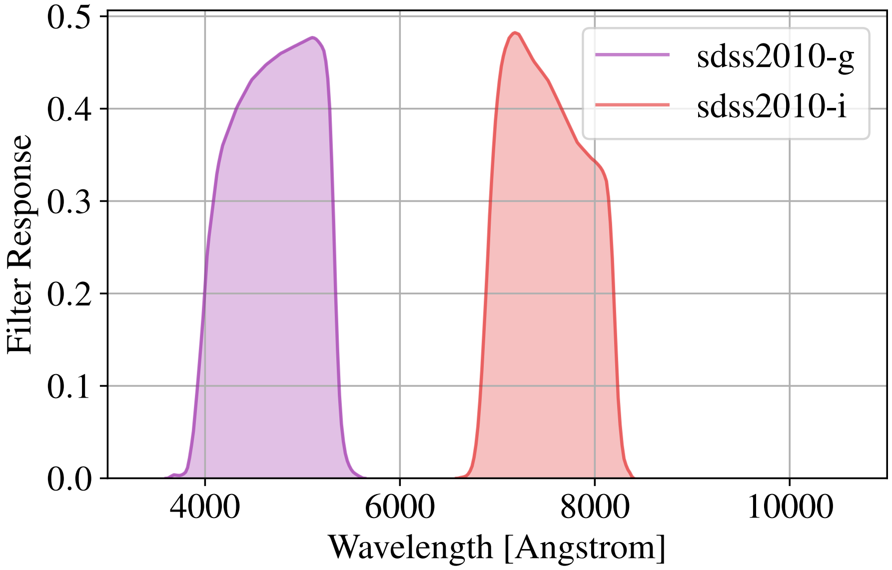

Figure 2. Filter throughputs of the SDSS-like filters mounted on SEO and Yerkes 40” telescope for our GC studies.

For this work, we focus on images of the M3 cluster (NGC 5272) in the constellation of Canes Venatici. In particular, we use a set of 55 images in *g* and 40 images in *i* band. Each of these exposures was 100 s long, for a total exposure time of 5500 and 4000 s in *g* and *i*-bands, respectively. One of the final mosaics is shown in Figure 1.

3.2. Asteroid Studies

The second case of interest of this work deals with the determination of photometric lightcurves of asteroids. This is a great alternative case for our students, as the main focus of this type of study is to analyze the variability in the brightness of a given astronomical source as a function of time, as opposed to the previous study case, where we focused on determining the surface brightness and colors of the GC members. Part of the results showed in this section, those referring to asteroid 15989, are published in the Minor Planet Bulletin (Sani et al. 2021b), showing the success of our collaboration. The results for the second asteroid presented in this section, asteroid 1637 Swings have been submitted for review to the Minor Planet Bulletin.

The data used for this study was acquired using the SEO 0.5-m telescope. The images are taken using no passband filters, and they follow the same basic calibration procedure as in the case of GCs to generate the science-ready images. In this case, instead of being interested in the measurement of apparent flux using a deep coadded image, we study the changes in the observed magnitude of the source of interest as a function of time, which helps us to determine its period and geometry.

`MPO Canopus` was used for the analysis of the target asteroids. This software was used to bring together the measured brightness of the asteroids on the images to create lightcurves. Once the lightcurves were generated, we proceeded to their analysis, using again MPO Canopus to estimate their periods and amplitudes. The science ready images were calibrated using dark, bias and flat field frame from windows command line. We made use of solar colored field stars from CMC- 15 catalogue to convert instrumental magnitude to R magnitude. Analyses were done using features of MPO Canopus to estimate the period and amplitude of the asteroid.

In particular we focus on two targets: Asteroid 15989, and 1637 Swings. Observations for asteroid 15989 were carried out over two nights and 374 data points were collected, using 120 second exposures. Observations for asteroid 1637 Swings were carried out over two nights and 255 data points were collected.

4. Results

4.1. Globular Cluster Studies

Using the data and calibration presented in section 3.1, we measured the magnitude in g-band and r-band of the sources in the M3 GC. The resulting CMD is shown in the right panel of Figure 3.

From our plot in figure 3, the turn off point can be measured. This is the point were the stars exhaust their main fuel; hydrogen and leave the main-sequence phase. By determining the mass of the main-sequence turnoff stars, we get the age of the cluster.

Future work will use this H-R diagram to find the age and distance to M3 by fitting models or isochrones to it.

4.2. Asteroid 15989 and 1637 Swings

Using the asteroid data presented in Section 3.2, proceed to the lightcurve analysis of our two sources of interest, which are shown in Figure 4 and Figure 5. The results for asteroid 15989, are published in Sani et al. (2021b). The lightcurve analysis showed a solution for the rotational period of $T = 5.528 \pm 0.006$ hours and with amplitude of $A = 0.57 \pm 0.05$ mag. This result was suggested by the strongest peak in the period spectrum of this asteroid. The results for asteroid 15989 agreed with earlier results published in Lightcurve Database (Warner et al. 2009b) as calculated by Pravec (2021).

The lightcurve analysis of the asteroid 1637 Swings showed a solution for the rotational period of $T = 10.226 \pm 0.009$ h and with amplitude of $A = 0.25 \pm 0.007398$ mag (Sani et al. 2021, submitted). This result was suggested by the strongest peak in the period spectrum of the asteroid. The asteroid lightcurve Database (Warner et al. 2009b) published a rotational period of 10.264 h (Brincat & Galdies 2018) for this object, in agreement with our results.

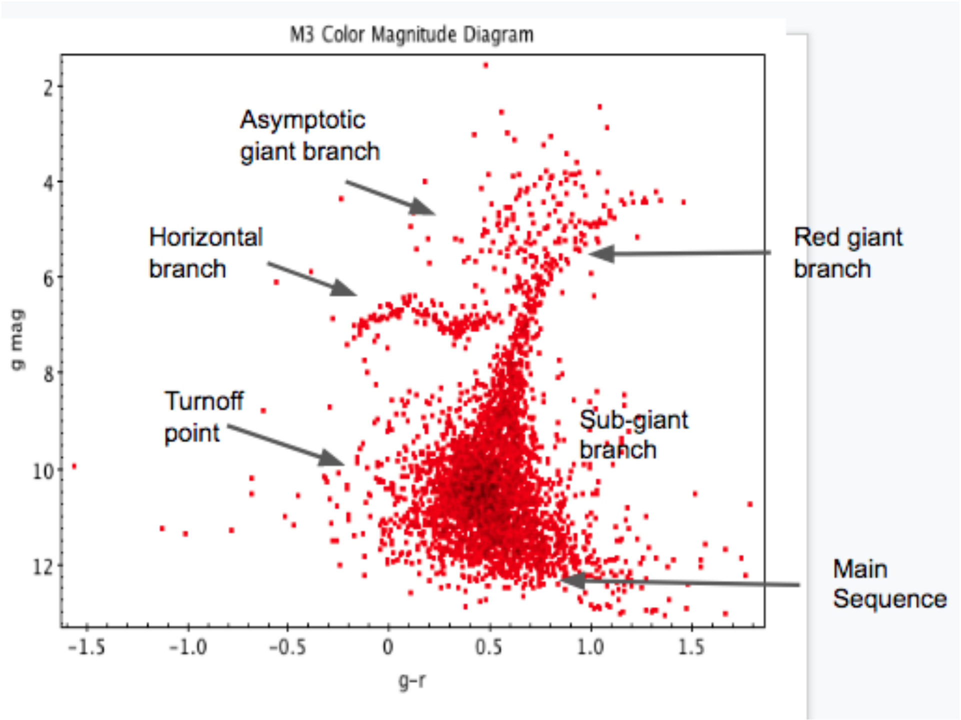

Figure 3. H-R diagram of the M3 globular cluster, as measured using the data presented in this work.

5. Conclusion

The search to expand understanding and collectively answer questions about our universe brought about the international collaboration among GLAS Education and Stone Edge Observatory (SEO) partnered with the WAROAD to create an intensive educational experience for astronomy teaching and public engagement. Globular cluster (GC) studies, a very active area of research was leveraged upon, as the perfect combination of entry-level astronomy and potential for discovery. It has included introducing upcoming scientists with data analysis tools in astrophysics to observe, reduce, and analyze globular cluster data from SEO. We have presented the results of the mosaics, our data reduction process, statistics of our data for our chosen globular cluster (M3), and the color-magnitude diagram (CMD) of our globular cluster. The primary authors of this manuscript have presented their results in conferences, including the Astronomical Society of Nigeria (ASN) and the Astronomical Society of the Pacific (ASP).

Our plans for future work will include characterizing the properties (ages, metallicities, and colors) of the stellar populations in our clusters. Also, continuing surveys on asteroid photometry and other new transient objects.

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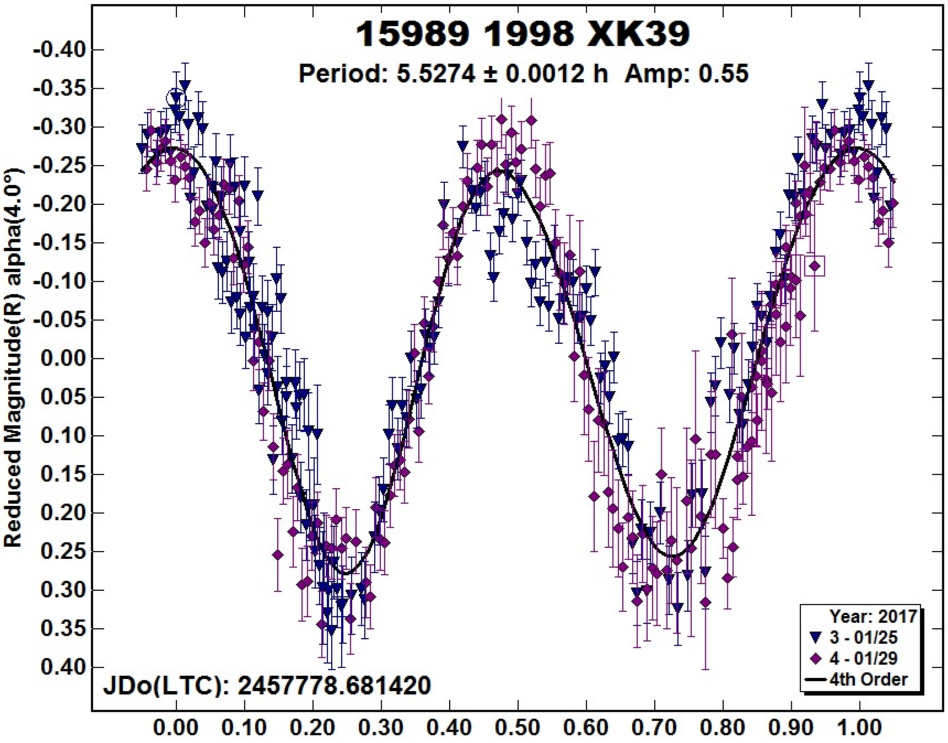

Figure 4. Lightcurve for asteroid 15989 as shown in Sani et al. (2021b). Over 374 data points were collected to create this lightcurve using 120 s exposures. Two sets of data points collected on 01/26/2017 (blue triangles) and 01/29/2017 (purple diamonds) are shown. The best-fit 4th order polynomial is shown as a solid line. The lightcurve, errors, and fit were determined using MPO Canopus.

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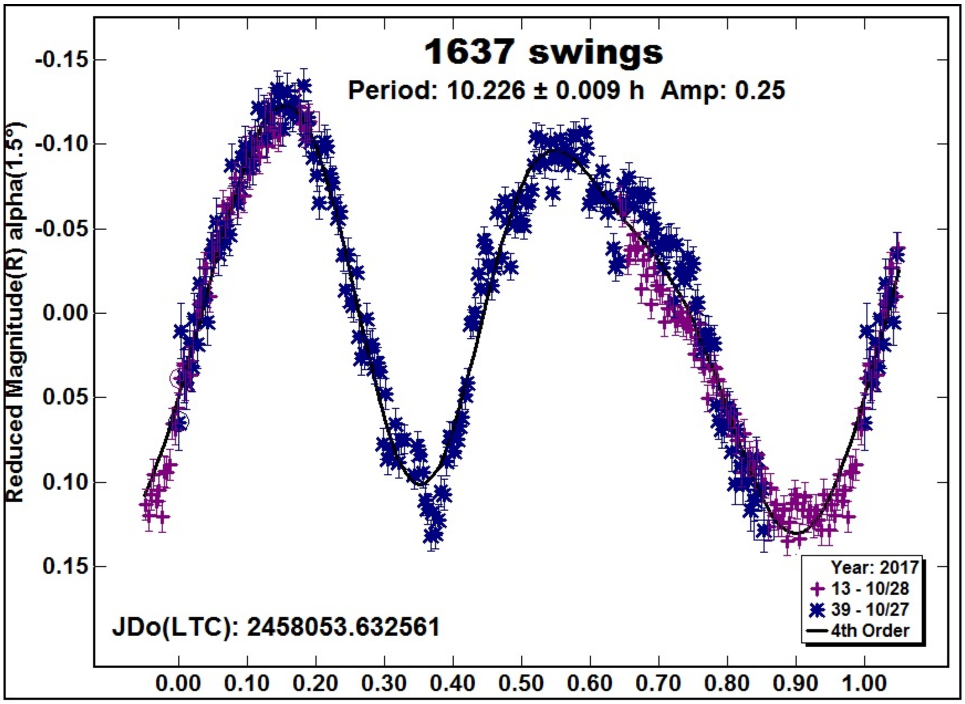

Figure 5. Lightcurve for asteroid 1637 Swings. Two datasets are shown, a set collected on 10/27/2017 (blue symbols) and 10/28/2017 (purple symbols) comprising a total of 255 data points using 120 s exposures. The best-fit 4th order polynomial is shown as the solid line. As in Figure 4, lightcurve, errors, fits and results were obtained using MPO Canopus.

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