Variable Star Observation and Search

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Abstract

Variable stars are stars that vary in their light output over time. We have used the on-campus observatory facility, as well as supplies purchased with a Sigma Pi Sigma undergraduate research grant, to locate, observe, and collect data on these stars. The main objective of the project is to learn to perform accurate CCD photometry while also to engage members of SPS with a long-term research project. Our goal is to match our gathered data to verified data recorded by the American Association of Variable Star Observers (AAVSO) and eventually to begin contributing original results to the organization. Results obtained from this project will also help to determine the best observing and calibration techniques for photometry in the heavily light-polluted skies of Philadelphia.

I. Introduction

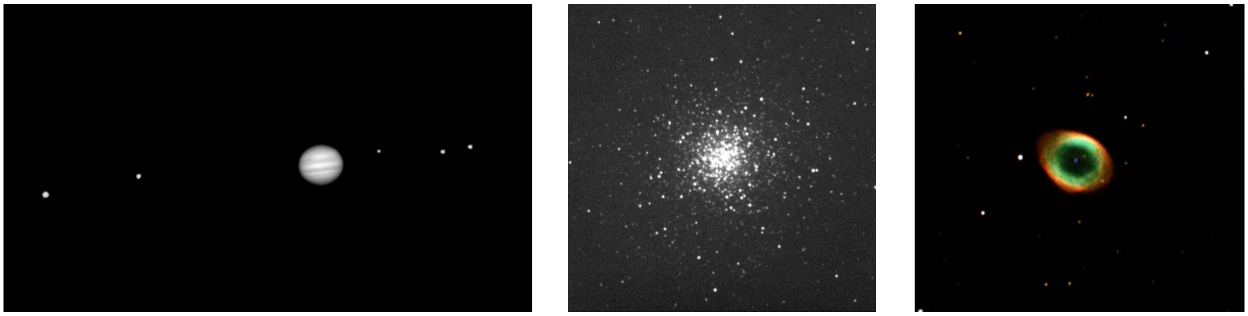
The Variable Star Observation and Search project began as a way for SPS members to work together on a research project of general interest. Anyone interested in learning to use a telescope, take astronomical images, or simply in learning more about observational astronomy was encouraged to participate.

Upon receiving a Sigma Pi Sigma Undergraduate Research Award, the proposal committee began to work with the Drexel's Astrophysics Group, learning the procedures to observe variable stars. With the help of Dr. Gordon Richards and astrophysics graduate student John Parejko, the committee made several trips to the on-campus observatory to learn basic operation of the telescope and CCD camera. This involved learning about celestial coordinates, gaining familiarity with the major constellations and prominent stars, and practicing telescope alignment and focus.

Our observational work is done at the Joseph R. Lynch Observatory. Located on the roof of Drexel's Main Building, it houses a 16" Meade LX200GPS telescope, currently the largest operational telescope in Philadelphia, along with several other small telescopes and CCD imaging equipment, including an SBIG ST-9 CCD camera. Once mastering basic telescope operation, we attempted CCD imaging and precise focusing on relatively bright, and easily-locatable celestial objects including planets, open and globular clusters, galaxies, and nebulae before moving on to variable stars.

Above: Proposal committee in front of the dome of the Joseph R. Lynch Observatory;
From left to right: A. Petrone, J. Mlack, A. Bolesta, & S. S. Mehta

Below: CCD images taken with the Lynch Observatory facilities.
From left to right: Jupiter and its moons, globular cluster M3, and color-composite image of planetary nebula M57



II. Background

Variable stars are stars that change in brightness over time. While most stars in the universe, including our own Sun, vary in brightness due to some degree of irregularity in their intrinsic processes, most of these variations are very subtle and cannot be observed from light years away. However, there are many stars whose intensity can vary over large magnitude values, and it is these variations that are of interest to astronomers as they can be seen and studied from Earth. There are over 50,000 confirmed variable stars listed in the 2004 edition of the General Catalogue of Variable Stars[1], and the list of potential variables continues to grow.

Information obtained by observing variable stars can help us determine the fundamental properties of such stars and classify them. For instance, a star-like object with a mostly constant intensity but with two distinct drops in brightness per cycle suggests that the object observed is in fact an eclipsing binary star system. A mostly stable object with sudden, sharp rises in radiative output indicates a pulsating or eruptive variable star, which attributes its variability to internal instabilities. On the other hand, stars displaying regular oscillatory variability would suggest that the star could be an RR Lyrae variable, if the star had a period of less than a single day, or a Cepheid variable if it had longer period oscillations.

Additionally, studying variable stars can also help us understand our galaxy and the universe by providing a way to measure distance, a highly difficult quantity to obtain in most astronomical work. Astronomers discovered that constant period of variability of Cepheid and RR Lyrae variable stars are directly proportional to the star's luminosity, which is a measure the total energy output of a star per unit of time. Comparing this luminosity value to the amount of light received by a telescope in the same unit of time, it is possible to work backwards to obtain the distance to the star. Such variable stars and other objects of known or calculable luminosity are often referred to as "standard candles." Variable stars are a particularly useful type of standard candles since they are relatively abundant, giving astronomers the ability to measure distances to objects such as globular cluster and even nearby galaxies, enabling astronomers to more accurately map the universe.

We decided to track variable stars with a relatively short, regular period, such as eclipsing binaries, RR Lyrae, and some Cepheid variables, initially selecting stars that have been extensively studied by other astronomers in order to compare our results with verified data. Specifically, we compared our data against light curves compiled by the American Association of Variable Star Observers (AAVSO)[2].

III. Observation

Having chosen specific stars to target, an observation schedule must be set for each individual star. Those with periods on the scale of one or two weeks, which were the longest period variables we studied, required observation several times per week, with a handful of images to be taken each night. Short-period variables, such as RR Lyrae stars, on the other hand, required long individual observation sessions, with dozens of sets of images taken each night since a substantial portion of the star's variation could be tracked over only a few hours.

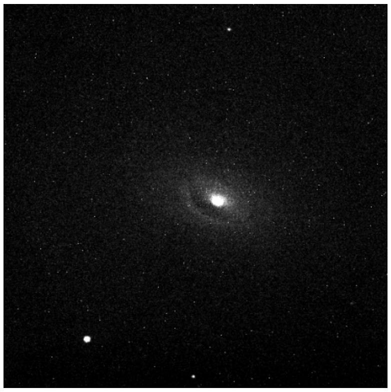
Each observation session begins with setting up the observation equipment, which includes the telescope, CCD camera, and auto-focuser unit. We first align the telescope on a handful of bright stars that are visible, and then choose one on which we fine-tune the telescope's focus. We then slew to the chosen object and begin the imaging process. For variable stars, we take 5-10 images in each color band we are considering (between R, V, and B bands) at an exposure time that prevents pixel saturation. This is either repeated as many times as is necessary in the session for the chosen star, or may be done for multiple stars in a given night. For each set of images, a set of dark frames is also required for image calibration. Finally, at the end of the session, a set of flat frames is taken for each color band that was used during the observation session (see next section for further description). As we develop the observatory facility further, we will have our guide telescope set up to track the sky much more accurately, making the process of following a particular celestial object over the course of a night far easier.

A group observation session in progress. Red lights are used in order to prevent loss of night vision.

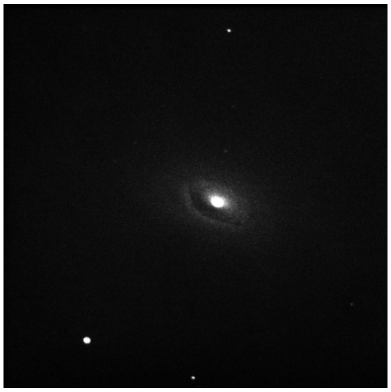
V. Calibration & Processing

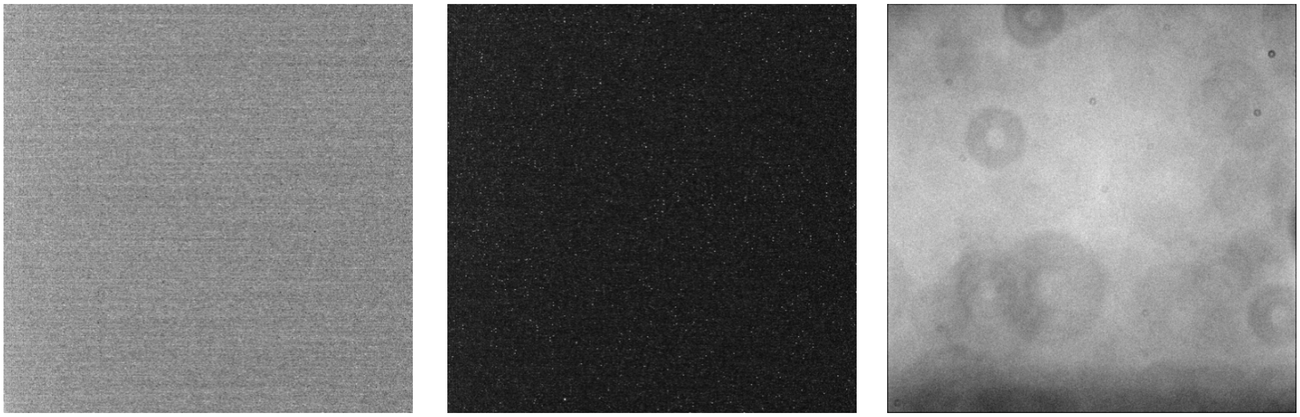
After taking raw astronomical images with a CCD (charge-coupled device) camera, it is necessary to calibrate them to remove non-data artifacts that exist due to thermal interference, optical imperfections, and interaction with cosmic rays. This is done by applying the dark, bias, and flat frames taken during an observation session.

The dark frame is an image that acts as a map of the thermal noise generated by the CCD and is taken with the camera shutter closed at the same temperature and exposure time as the raw image. The bias frame is a zero-second exposure image that contains image readout noise as well as electronic noise that is generated by the CCD. Generally, since the dark frame already contains the bias component, the bias frame is not a vital component in image processing; it is, however, essential in the generation of scalable dark frame, which we do not use for this project. While the bias and dark frames account for undesirable noise generated by the CCD, the flat frame is used to remove artifacts caused by flaws in the optics of the telescope or CCD. Flat frames are commonly used to eliminate illumination patterns and shadows or donuts, which are caused by dust particles that appear out of focus in the image. It is taken while pointing the telescope at a uniformly light source field and is exposed until the average photon count is about half of the CCD well depth. Since flat frames are generally taken at different exposure times to the raw images, it is necessary to take a separate set of dark frames to calibrate the flat fields.



An image of the galaxy M64 before (left) and after (right) calibration and processing. Notice the increased clarity of the gaseous disk and the lack of thermal noise in the final image.





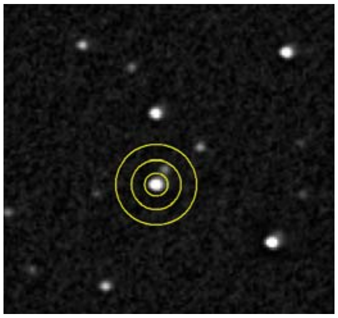
Examples of the bias, dark, and flat calibration frames. Note the hot pixels due to thermal noise in the dark frame and the dust donuts in the flat frame that are removed through processing.

Before applying the calibration frames to the raw images, it is necessary to combine them appropriately in order to reduce noise, eliminate hot pixels and exaggerated pixel counts due to cosmic rays, and account for image-to-image variations. For all dark frames taken at identical CCD temperatures and exposure times, we can perform a median combine in order to receive a master dark frame. Next, subtract the appropriate master dark frame from each flat frame and median combine the modified flats to obtain the master flat field frame, which results in a high signal-to-noise calibration image. Finally, subtract the appropriate master dark frame from each raw image and then “divide” by the master flat field to obtain a calibrated astronomical image. Division, in the case of image processing, refers to floating-point division of each individual pixel value of the image by the value of the respective pixel in the flat frame. Additional processing such as image stacking can be performed in order to increase the signal-to-noise ratio and improve photometric results for each set of observations.

V. Data Analysis & Light Curve Generation

A light curve is a plot of the light intensity of a celestial object over time, usually using a Julian date. Lights curves can help to determine certain properties, intrinsic or extrinsic, of celestial objects. Specifically for variable stars, the period and amplitude of variation can be determined, which are used to classify them. As discussed, since certain variable stars fluctuate consistently due to intrinsic properties of the star, they can be used as “standard candles” to help gauge distances to distant objects in which they reside.

Using calibrated astronomical images of variable stars, we begin by measuring the flux of the star in each image through a method called aperture photometry. In a digital image, because of imperfect optics and atmospheric interference, the light from stars is distributed over a point spread function, which is usually approximated with a Gaussian fit, which is commonly known as a bell curve. The full-width at half maximum (FWHM) of the fit, which is the width of the portion of the bell curve that is greater than half of the total height of the curve, is used as a quantitative description of the astronomical seeing of the observation. Since the star light is distributed over this curve, which depends on the seeing conditions, the FWHM helps us to determine how much of the star light on the image to consider. In aperture photometry, the intensity of a star at each pixel of the image is summed in a circular area of radius 1.5 times the FWHM from the star's center. Additionally, the brightness of the sky is determined by summing pixel values in an annulus around the star, ensuring that there are no other stars nearby; from this sum, an average sky intensity value per pixel can be found. By subtracting the average sky intensity multiplied by the number of pixels in the star disk from the total pixel count of the star, one receives a first-order approximation of the flux of the given star. This flux value may be scaled appropriately if there exists a nearby reference star with a relatively constant intensity in order to accommodate variations in seeing over the course of observation.



Example of a star radius in which the star intensity value is summed and the surrounding annulus.

Finally, it is necessary to convert this flux value into an apparent magnitude value. Apparent magnitude is a measure of the brightness of a celestial object as viewed from Earth, with lower values indicating brighter objects. This is essential for variable star photometry since apparent magnitudes are comparable with any other kind of object, whereas flux depends on the parameters used when taking the CCD image. The apparent magnitude of a source imaged in a specific color band, x, can be calculated using the formula:

$$m_x = -2.5 log_{10} \left(\lambda_x \right) + C_x$$

where λ_x is the flux calculated through the given color band and C_x is a constant that depends on the properties of the color filter used. Another, sometime easier, method is to compare the flux of the variable with that of another nearby star, which is usually in the same field as the variable, provided that it has a relatively constant brightness and a known absolute magnitude. Given these parameters, we use the following formula to calculate the apparent magnitude of the variable:

$$m_1 = m_2 - 2.5 log_{10} \left(\frac{\lambda_1}{\lambda_2} \right)$$

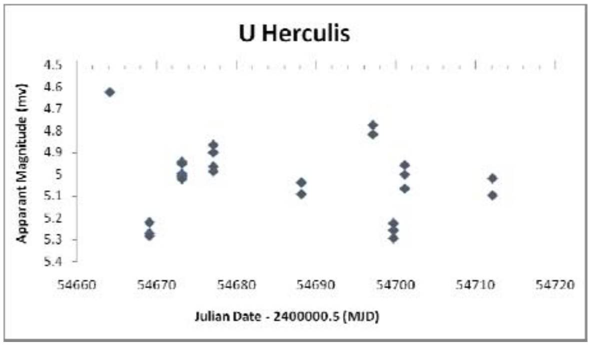
where m_1, λ_1 and m_2, λ_2 are the magnitudes and fluxes of the variable star and the reference star, respectively. Given the magnitude of the variable star at each observation and the precise time of observation, it is then possible to plot these values and construct a light curve for the star.

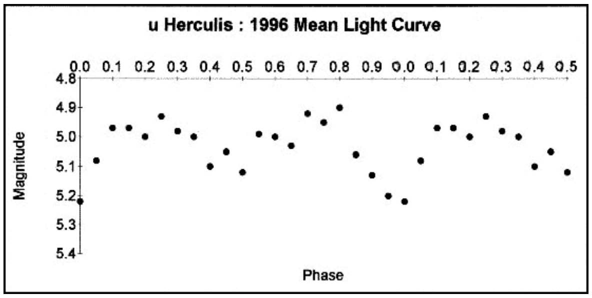
VI. Results

Our initial research consisted of imaging three different types of variables that have been extensively monitored in the past. We give some brief information on each star we observed and the light curves we obtained after analysis. These results have been presented at the research poster session of the 2008 Sigma Pi Sigma Quadrennial Congress at Fermilab.

u Herculis

u Herculis is an eclipsing binary, which appears to be a single star to the naked eye, but is distinguishable as a double star in high resolution CCD images. Located to the right of the body of Hercules, it has a magnitude range of 4.6 - 5.3 with a period of 2.051 days. Below, we have an image of the star field around u Herculis, u Herculis being the brightest star in the frame, a computed light curve from our experimentally acquired data, and a third party light curve generated by the Society of Popular Astronomy[3].

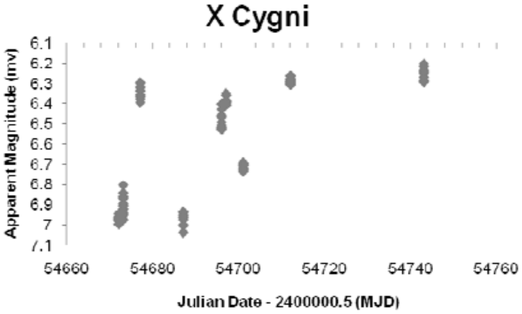


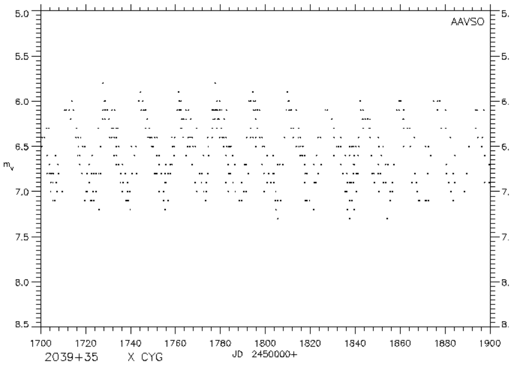


X Cygni

X Cygni is a Cepheid variable star that varies from magnitudes 5.6 to 7.8 in a period of 16.38 days. The variability of Cepheid variables is caused by the expansion and contraction of the outer atmosphere of the star due to the ionization of helium. This fluctuation rate, which is generally between one and 70 days, occurs proportionally to the star's absolute magnitude. For this reason, Cepheids have become so-called "standard candles" since with the knowledge of the absolute magnitude of an object, one can easily calculate its distance. Cepheids have become extremely useful in determining the distances to local galaxies.

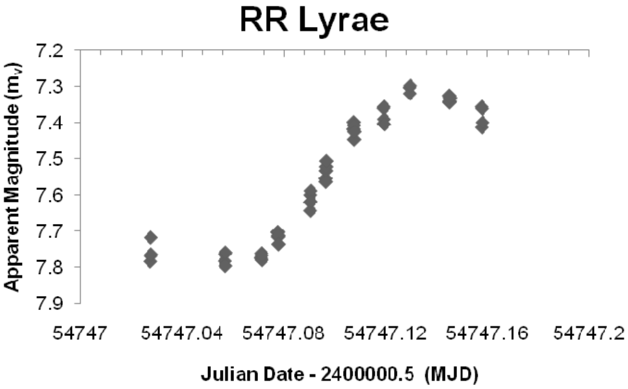
Below, we have a small star field containing X Cygni, a light curve generated from our experimental data, and a complete and verified light curve from the AAVSO[2] for comparison. Our difficulty in developing a light curve for this star was due to the relatively long period of the star and our inability to image frequently enough due to poor atmospheric conditions.

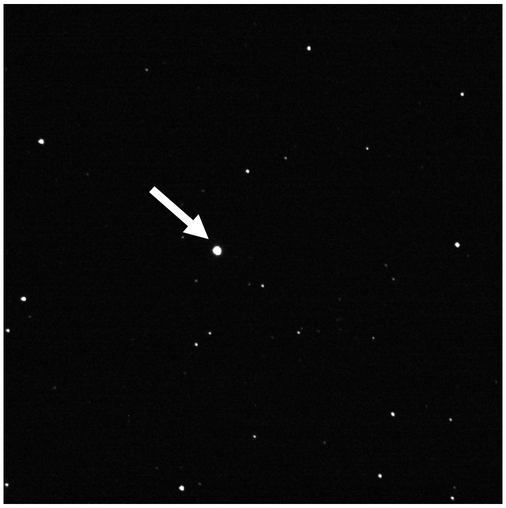


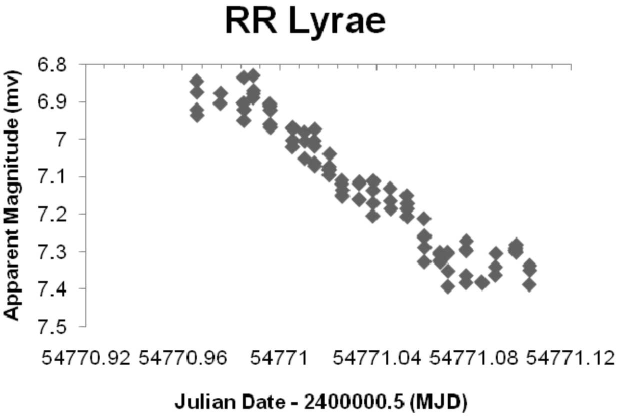


RR Lyrae

RR Lyrae is the namesake for a variable star classification that regularly oscillates at periods shorter than a day. RR Lyrae variables are caused by a similar intrinsic process in the star's atmosphere as Cepheids, but the fluctuations occur much more rapidly. For this reason, RR Lyrae stars also used as standard candles, but primarily for globular clusters within our galaxy since they are older, smaller, and dimmer than Cephieds. RR Lyrae itself varies from magnitude 6.7 to 8.0 in about 13 hours. Below is a view of the star field containing the variable and two light curves, representing different portions of the full curve.







VII. Conclusions and Future Work

This project thus far has taught us a great deal about general astronomy, astronomical imaging, and photometric techniques. We have successfully been able to image, process, and analyze data collected at the Lynch Observatory. We have learned of a sufficiently accurate photometric method with which we can process our images, and we have generated light curves that, in most cases, match verified data remarkably well. Philadelphia, being an extremely light-polluted area, has highly volatile atmospheric conditions. Ignoring frequent cloud cover which hindered our observation of longer period variables, we discovered that the conditions, even on clear nights, differed drastically. It will be necessary to investigate methods of resolving this difficulty. However, this can also be avoided by tracking only very short period variable stars, such as RR Lyrae variables. It is clear, given our results, that we can most easily obtain very complete and accurate light curves for such stars, and thus they are ideal observation targets for our sky conditions. Thus, as we continue this project, we will begin focusing specifically on RR Lyrae variables and participating in AAVSO's RR Lyrae Observation Program, which involves studying known RR Lyrae variables for which there are little or no submitted data. Additionally, in the interest of searching for undiscovered variables stars, we hope to begin a program of regularly imaging globular clusters which are likely to contain RR Lyrae and Cepheid variables and monitoring them for any intensity changes of stars in the outer regions.

We hope that the progress we have made thus far on our project will act as the ground work for future projects by students of the Drexel University Society of Physics Students that will lead to contributions of data and light curves to the AAVSO or other professional organizations.

VIII. Financial Report

Item	Price
Stellarvue SV102ED for Telescope Guiding	$995.00
Losmandy Rail Mounting Rings	$40.00
Meade Deep Sky Imager Pro III for Telescope Guiding	$699.00
RS-232 to USB Adapter Cables	$40.90
Red Flashlight	$26.95
Bisque TheSky6 Student Edition Astronomy Software	$49.95
AIP4WIN Astronomical Image Processing Software	$99.95
Total	$1951.75

IX. Acknowledgements

The Drexel University Society of Physics Students would like to thank the Drexel Physics Department, Dr. Gordon Richards, and graduate student John Parejko for their help and support with this project. The chapter would also like to thank SPS National and Sigma Pi Sigma for awarding us a Sigma Pi Sigma Undergraduate Research Award, which made this project possible. Finally, we thank all those from the Drexel University Society of Physics students who contributed to this project, including Jerome Mlack, Anna Petrone, and Alexander Bolesta.

X. References

[1] http://www.sai.msu.su/groups/cluster/gcvs/gcvs/
[2] http://www.aavso.org/
[3] http://www.popastro.com/sections/vs