Monitoring Visual Accretion to Detect Rare Low-Flux States of Intermediate Polars

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Astrophysics Thesis

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Abstract

Intermediate polars are variable binary star systems where one member of the system is a white dwarf with a strong magnetic field. These stars form 'accretion curtains' along the magnetic field lines as the white dwarf siphons material off of its partner star. Intermediate polars, including the subset of low-luminosity intermediate polars, have been known to go into a 'low state', indicating a reduction in the accretion rate. Only one deep, pointed X-ray observation has ever been made of a low-state intermediate polar, but making these pointed X-ray observations can yield new knowledge about these intermediate polars and binary star accretion. In this paper we introduce a monitoring program used to watch the visual flux of intermediate polars and low-luminosity intermediate polars in order to trigger a pointed X-ray observation of the star when it enters a low-state.

Introduction

The universe, as old as time itself, moves both in ways too slow to perceive and in ways so fast that in the blink of an eye it's gone, with scientists left wondering what they saw to begin with. Variable objects have stumped astronomers for as long as there have been astronomers, and it can feel like bare luck to have observed them. Any time the seemingly unchanging sky shifts, people here on Earth pay attention, from stellar explosions being read as omens to slight dimming of stars leading humanity to discover its first exoplanet. However, it takes a keen eye to notice these changes and an even keener telescope to capture it.

Cataclysmic variables (CVs) are one such variable object, describing binary star systems containing a white dwarf and a larger, still-living star. When material strays outside of the Roche lobe of the larger partner star, it 'falls' onto the white dwarf, accumulating to form an accretion disk around the white dwarf. Magnetic CVs (mCVs) are CVs where the white dwarf part of the binary system has strong magnetic fields (about 10^6 - 10^8 G) that form 'accretion curtains' along magnetic field lines. This can manifest two ways. In polars the accretion disk is completely disrupted and the spin period of the white dwarf is synchronized with the binary orbital period. In intermediate polars (IPs) the magnetic field is not strong enough to disrupt the entire accretion disk, only influencing the center of the accretion disk around the white dwarf. Due to this magnetic field, the spin period and binary orbital period are not synchronized.

By nature, both kinds of polars are variable in flux. A part of that is that reductions in accretion rates can result in dramatic decreases in optical and X-Ray flux. This is a “low-state”, which we define as a significant drop in brightness below the average for that CV. These low-states are so extraordinarily rare that only two have ever been observed in X-Rays: Fo Aqr (Kennedy et al. 2017, 956-967) and V1223 Sgr; and only Fo Aqr has a deep, pointed X-Ray observation. There are some theories as to what causes these decreased flux states, however with so few observations it is difficult to say for sure why it happens. Looking at the data, it is clear that pointed X-ray observations of low-state IPs are needed to be able to understand these objects.

As mCVs are subclasses of CVs, and IPs are subclasses of mCVs, IPs have a subclass known as low-luminosity IPs (LLIPs) that demonstrate X-ray luminosities about two orders of magnitude fainter than most other IPs. These LLIPs are already very low flux, and their luminosity already lies below even the low state of FO Aqr. Therefore, it was not expected that LLIPs could have low states where they transition to even lower flux. However in June 2017 the LLIP DO/YY Dra was found to be in a low state, proving that it is possible. (Andronov 2017)

We seek to capture X-ray data of an IP or LLIP in a low state using the XMM-Newton telescope. Recording an IP in a low state will double the amount of deep-pointed X-ray observations of low-state IPs, and recording an LLIP in a low state will be the only observation of its kind. This could give us new insight into accretion mechanisms, a process that is poorly understood due to a lack of data. Dr. Aarran Shaw (Shaw 2019) has put in a request for a quick trigger of X-ray observations following a decrease in visual magnitude of one of the target stars being monitored. The main content of this document will be monitoring IPs and LLIPs for a decrease in magnitude using the Great Basin Observatory (GBO) in order to be prepared for a summer trigger of the observing request of the XMM-Newton telescope.

Theory

When it comes to monitoring a variable object over time, a light curve is a valuable tool in the astronomer's arsenal. A light curve is a graph of the flux coming off of a star over time and is the perfect way to detect a large increase in the magnitude of a star (meaning a decrease in flux). The light curve will allow for the establishment of a baseline of the magnitude of a target star so that the increase in magnitude can be properly identified in order to take the X-ray measurement of the low state.

The process of analyzing light in the night sky is called photometry. Photometry and photography share a common root due to their common medium: light. Photometry behaves much like photography in that it captures the light in front of the camera. However, when the light can be many light years away, the process is harder than simply snapping a photo. Modern photometry uses a charge-coupled device (CCD) that consists of a block of many 'pixels', which are designed to count photons. To take photometric data the CCD is pointed at the part of the sky where data needs to be acquired, and allowed to face that sky for a certain amount of time. This exposure time is a balance between capturing as many photons as possible to get a more detailed image of the sky, including fainter targets, and leaving it exposed too long and risking oversaturation as too many photons hit a pixel for it to contain.

Photometry data is not immediately usable. When the CCD collects photons, it also collects background radiation, photons that are 'stuck' in the CCD, and dead pixels. To solve this problem the image data is calibrated with three kinds of images called frames. A bias frame is taken with an exposure time of zero and with the shutter on the camera closed. This frame accounts for read-out errors, dead pixels and other errors inherent to the CCD. The second frame is the dark frame, which is taken with the shutter closed for the same exposure time as the image. This removed thermal noise generated by the detector. The final frame is the flat field, created by illuminating the CCD with a uniform light source that compensates for obstructions in the light path and varying quantum efficiencies of pixels across the detector. However, the flat field is not used raw. The flat field needs to be normalized and have the dark frame subtracted from it as well. While bias and dark frames are subtracted directly from the raw image, the flat field is divided from it as shown in equation (1).

(1) $$\text{Calibrated} = (\text{Raw} - \text{Bias}^{1} - \text{Dark}) / \text{Flat}$$

Using this photometry data it is possible to count the number of photons in a star and use that information to obtain the relative magnitude of the star using equation (2), where N is the number of photons captured in the star (N_{src} being the number of photons in the target star), and m is the magnitude of the stars.

(2) $$(m_{src})_i = -2.5\log_{10}\frac{Nsrc}{Ni,ref} + m_{i,ref}$$

This calculation is done for three to five reference stars, in which $N_{i,ref}$ is the number of photons in a specific reference star and $m_{i,ref}$ is the magnitude of that star, and then the results of the formula for each reference star are averaged. This can be a lengthy process to do by hand, even with the software available for viewing and analyzing this data. However, with the technology available in the modern age, there is no need to do this task by hand.

Methodology

Due to the limited amount of time this project can have with the XMM-Newton telescope, the trigger for X-ray observations will be based on the observations made by the American Association of Variable Star Observers and observations made by the Great Basin Observatory telescope, a 0.7m robotic telescope located in the Great Basin National Park. The University of Nevada, Reno has a relationship with the GBO such that they are always accessible to students and faculty of the University, making them a good candidate for monitoring the IP and LLIP objects. Starting on February 12th, 2020 the GBO has been taking V filter data of six target

[1] The bias has been included in this equation for completeness, however in the GBO telescope being used the bias frame is included in the dark frame, so only the dark needs to be subtracted.

candidates: BG CMi, DO Dra, DW CnC, GK Per, V405 Aur, and V2306 Cyg. Photometry is a long task, and a month's worth of data for one star would be a daunting task, much less for six different stars. That is why I have sought to automate this process, and have been able to track the light curve of the intermediate polar DW Cnc.

The analysis was done using a fully autonomous program in Python using the astropy library (Robitaille et al. 2013, A33). From the user the program expects the location of the target star in decimal degrees, the image data, and the calibration files (the dark frame, bias frame, and flat field images). The user can also specify some settings for the photometry process. For instance, the program is capable of finding reference stars and their radii. However, this may not always be what the user wants, so the user is able to use specific reference stars and choose to use three times the full-width half-maximum (FWHM) as the radius.

As shown in the visualization of the process in Figure 1, once the program starts the first thing it does is calibrate the image file to remove background radiation and noise from the data. Then, depending on the settings, it re-centers itself on the target star, translating world coordinate system (WCS) degrees to pixel locations, and finds the radius of the target star and then uses that radius to add up all the counts found within the area of the star. The program will also find the average background radiation in the form of the median amount of photons in a "blank"[2] portion of the sky. Then the program will either find possible reference stars or read in the chosen reference stars from a file. When the program finds the stars, it uses the SIMBAD[3] database to get the known magnitude of that reference star. From there, it is simple to use equation (2) to calculate the target star magnitude for every reference star, and then get the average calculated magnitude as the final answer. Currently, the program is only set to use the V magnitude values from SIMBAD and can only calculate the V magnitude of a star, however in the future the user will be able to select which magnitude type they want to use.

[2] The blank sky value is derived using astropy's Background2D function that uses sigma-clipped statistics in each mesh of a grid that covers the data to create a low-resolution, and possibly irregularly-gridded, background mat (Background2D 2020). The value is then set to be the median number of counts in a pixel in that simulated background grid.

[3] This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

Not all reference stars are equal, however. The best reference stars are near the target star and of a similar magnitude as the target star. When using reference stars that are farther away and several magnitudes more or less bright than the target star, error is introduced. The program calculates the standard deviation of all of the magnitude calculations and flags the user if it believes there are outliers among the reference stars. If the error is larger than an acceptable amount, currently set to be the magnitude divided by 20, the user can remove the outliers, and the program will save their choices for the next dataset. Then, this program can be run for every photometry image that the GBO takes, allowing for the creation of a light curve and for easy, autonomous monitoring of the target stars for a decrease in brightness.

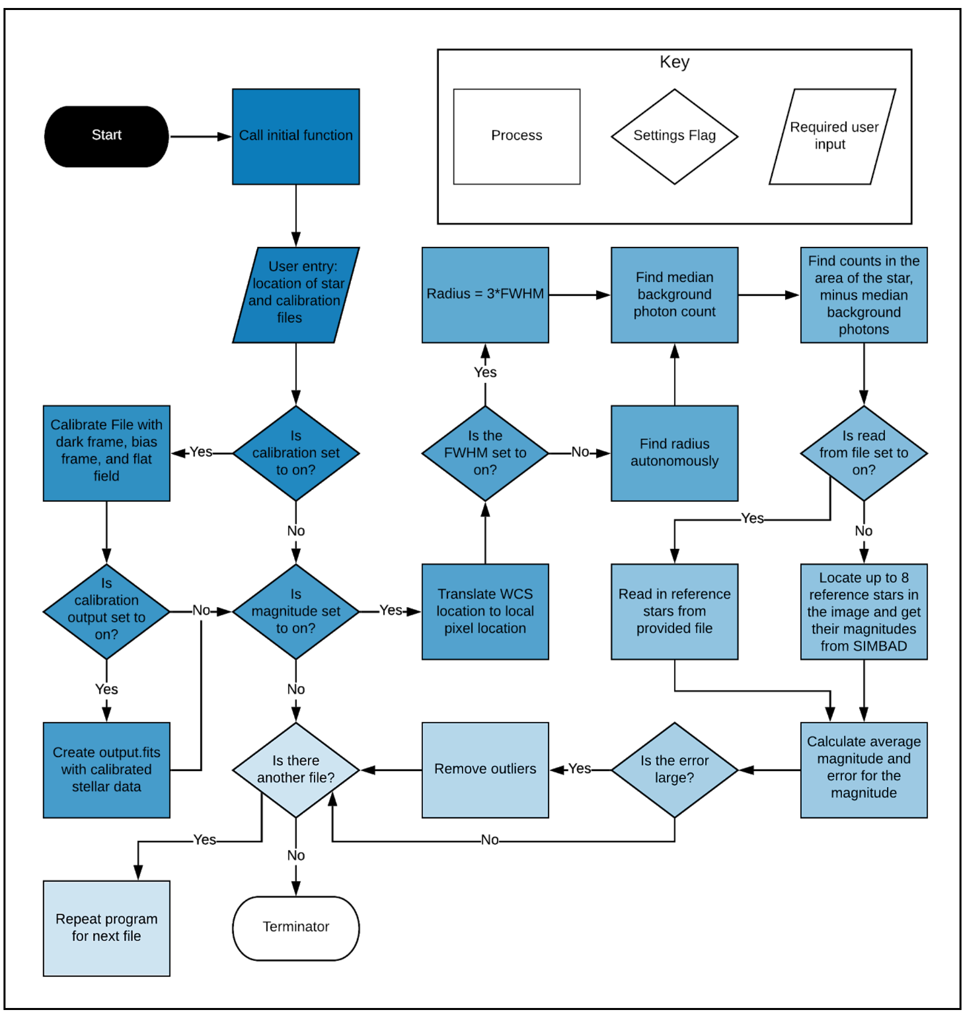

Fig. 1: A block diagram showing the autonomous photometry process.

Results

Using the GBO telescope and the photometry program, we were able to successfully monitor the flux of DW Cnc, imaged in Figure 2 along with the reference stars used, in the V magnitude for one and a half months. The magnitude hovered in between 15 and 16 mag, dipping slightly lower than 16 mag for two days. The error bars are calculated using standard deviation from the magnitudes calculated for each reference star during the photometry process.

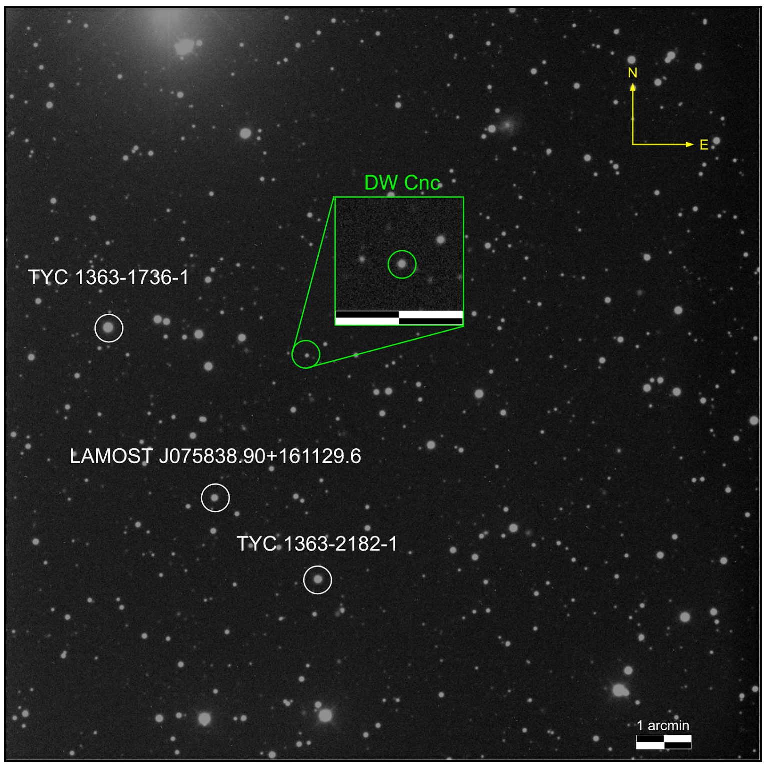

Fig. 2: Calibrated image data from February 15th. DW Cnc is circled in green, and the reference stars used for photometry are circled in white.

For three days in the middle of observation there was a malfunction with the GBO which prevented the capture of useful data. Additionally some days data could not be collected by the GBO, possibly due to bad weather or that our observations did not make it into that night's observing queue. But overall the light curve, shown in Figure 3, is a good representation of DW Cnc's activity over the observing period.

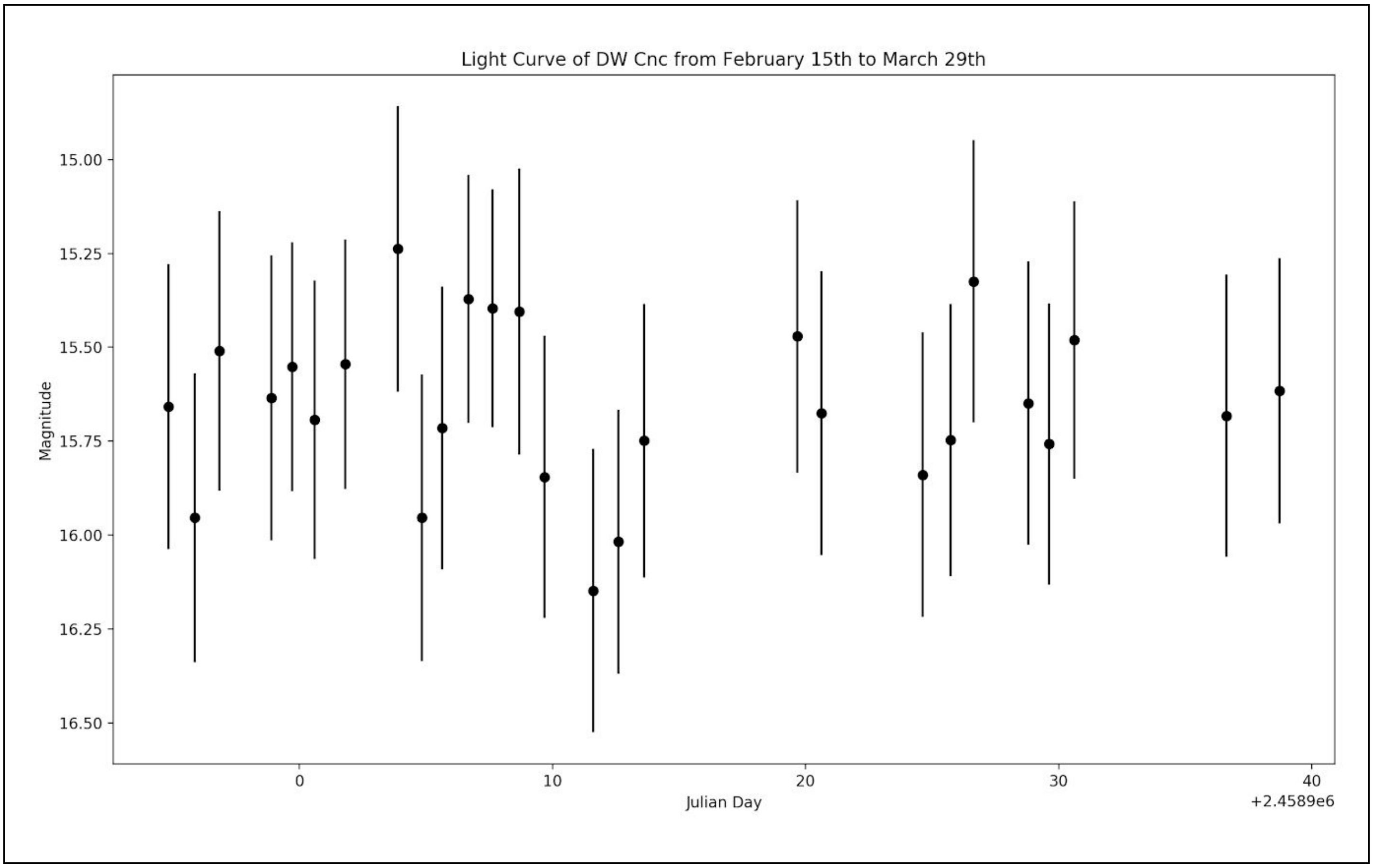

Fig. 3: The light curve of DW Cnc showing magnitude over a period of a month and a half.

Discussion

The magnitude of the star remained stable throughout observation, as expected for a star not currently undergoing some type of variable activity. DW Cnc has not gone into a low state in the time it was being observed by the GBO, although it has been shown to go into a low state previously, making it an excellent target (Montero et. al. 2020). Shown in the light curve above, the standard deviation of the light curve data is somewhat high. While this margin of error is acceptable for this monitoring program, it will likely need to be lowered before this program can provide more reliable results. This can be accomplished by taking a weighted average of each of the magnitudes calculated by using each of the reference stars. By calculating the error of each individual magnitude, more accurate measurements can be given more weight. Even with the large error bars, it is clear that the star is maintaining its original magnitude.

In order to quantify that the star is not currently going through a variable state a common measure is to calculate the reduced χ^2 value of the light curve using equation (3).

(3) $$\chi_r^2 = \frac{\sum_i \left(\frac{(m_i - \overline{m})}{\sigma_i}\right)^2}{N-1}$$

The reduced χ^2 value formula finds the variation in the magnitude measured each night (m_i) and the mean magnitude ($\overline{m}$) and then normalizes it by dividing over the error for the night (σ_i) and squares that number to prevent negative values. Then the whole calculation is divided over N-1, where N is the amount of nights of measurements. This value is approximately 0.13 for the light curve of DW Cnc. The astronomy community widely considers 3 the threshold for meaningful variability, and so this value quantifiably shows the lack of variability in the star during this observing period.

While a relatively unchanging light curve may not be the most exciting result, this light curve is a proof of concept for autonomous photometry. Being able to monitor the magnitude of a star in real time will be critical when it comes time to trigger an X-ray observation of an IP or LLIP. The baseline magnitude of DW Cnc is now known to be in the 15 to 16 mag range, so if it is detected at around 17 or 18 mag it will be an easy decision to take the X-ray observation.

Future Work

This is only one small part of a much larger project. In the future, when one of the target stars experiences a drop in flux, we will be able to take an X-ray reading of it in the hopes of gaining data from a low-state IP or LLIP. From there the data can be analyzed to advance the study of these rare stellar objects in a way that has only ever been done once before. There are also many more IPs to be observed with the GBO telescope that this pipeline can be applied to.

The program created for the analysis of this data still needs to be polished for general use. The next steps will be to add more settings and ways of seeing into the program itself. This program will go on to help all astronomers seeking to use the Great Basin Observatory telescope, starting with students pursuing astrophysics studies at the University of Nevada, Reno.

Acknowledgement

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