Differential Photometry of High Mass X-ray Binaries and Be Stars and Determining Standard Stars

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Abstract

Building off of the previously established Hα index (Joner & Hintz 2015), I use differential photometry to study high mass x-ray binaries and Be stars using the Hα index to define their level of activity. Specifically I focused of Cygnus X-1 and X Perseus. I took data on Cygnus X-1 (X Perseus will be studied later in the year) to look at its long and short term activity. Data analyzed using differential photometry is merged with previously collected spectroscopic data to show a seamless flow of results between techniques. I also defined the Hα values of 10 stars in the frame of Cygnus X-1 allowing us to keep the telescope in a single spot and collect much more data. Further study of the 10 internal frame standard stars shows a possible new variable star and emission object.

1 Introduction

Although we look at them almost every night, our pondering of the stars is usually short and insignificant. When scientists do begin to dig deeper into the queries of the stars we realize just how little we know about them, especially their life cycles. By studying a star at any point in its cycle we can piece together details of its life, which leads to a better understanding of stars as a whole. I am focusing on the middle and very end of the cycle by studying High Mass X-ray Binaries (HMXB) and Be stars respectively. In order to gain information on the two objects I perform photometric observations to collect data on the spectroscopic level of detail. I analyze the photometric data using a technique called differential photometry. This involves comparing the magnitude of the variable star to one with a constant magnitude to ensure the change in magnitude that we are measuring is true. I also will define several more standard stars to optimize data collection. To collect data I use the 8" diameter robotic telescope on the fourth floor of the Eyring science center. The telescope is still in the testing stage of system operation, therefore taking data using the telescope allows us to make the telescope fully operational.

1.1 Photometry and Spectroscopy

Photometry is the study of the intensity of light coming from a star or system. It is the easier of the two techniques as it takes less time and more commonly used filters. Widely practiced, photometry gives information on the brightness of the star and possible activity involving fluctuating magnitude. One of the most useful pieces of information that can be derived from this technique are light curves: a plot of the magnitude of the star versus time.
Spectroscopy involves studying the spectra of the star. Even though it takes a lot more time and skill to collect the spectra data, spectroscopy reveals a lot more about the star or system, including the temperature, angular momenta, and chemical composition.

1.2 High Mass X-Ray Binary

A high Mass X-ray Binary (Figure 1) is a binary system consisting of a high mass component and an x-ray component. The more massive component sits in the ‘middle’ of the revolution of the x-ray component (a white dwarf, neutron star, or black hole). There may be some slight movement of the high mass component due to the gravitational pull of the x-ray component as well. As the revolution of the x-ray component varies in distance to the high mass star, the outer layer of the high mass star is pulled off. This material then creates an accretion disk around the x-ray component and, when coupled with a black hole or neutron star, perpendicular shooting jets. The two HMXB that I have been studying include V1357 Cyg, more commonly known as Cygnus X-1, and X Perseus.

Cygnus X-1 consists of a blue super giant star and a black hole, which formed as a result of the collapse of a star $20_\odot$. It was the first widely accepted black hole discovered because the x-ray signals coming from this object are unusually strong.

X Perseus is composed of a Be star and a neutron star. Be stars will be further discussed in the next section.

1.3 Be Stars

Be stars are volatile stars just past the B spectral classification of stars. A B star is a main-sequence, massive star that is slightly cooler and less massive than the largest and hottest spectral classification of stars, O. For reasons not well understood, B stars progress into Be stars and, when they do, Be stars begin to eject their outer layer in bursts. Be stars have an unusually high equatorial rotation velocity of $200\,\text{km/s}$. One of the proposed and widely accepted theories as to why Be stars eject some of their matter is that their exceptionally high spin velocity is too great for the gravitational pull of the star, which causes some material to be thrown off. Ejected matter then forms a circumstellar disk around the star. This disk is the cause of the emission instead of absorption lines. It is not known if the volatile activity of the star is periodic or not.
2 Question and Objective

The goal of most operations today is to streamline a process. My research does not fall far from this, as my goal is to come to conclusions which have previously been made, but in more efficient ways. There are two main ways in which I will try to make this happen: seamless merging of spectroscopic and photometric data, and calibration of standard stars in the field of Cygnus X-1. Achieving both goals will save time taking data and simplifying data reduction. It will also help us answer the question: can we mesh photometry and spectroscopy into a seamless line of data and find short term periodic activity?

2.1 Significance

Photometric observations are much less time consuming than spectroscopic observations but do not yield as much data. To merge the two techniques, obtaining the same results as spectroscopy, but with the lesser techniques of photometry, would allow astronomers to save a lot of time and money. In order to do this we collect data of Cygnus X-1 and X Perseus to build long term activity plots of both objects. Plots of activity help us understand the behavior of Cygnus X-1 and X Perseus.

In addition, my research will help to identify standard stars in the same fields as the target variable star. All standard stars have stagnant h-alpha values and if astronomers know the h-alpha values for stars inside the desired frame then the telescope can remain stationed in that frame instead of wandering and still collect the same amount of data. Standard stars are a necessary component of differential photometry; if there are no standard stars in the field, astronomers must find them elsewhere in the sky which will take up time and money. This development will also allow astronomers to collect data on nights during which weather may have otherwise been an issue.

This research will help enlighten astronomers on the curiosities of the life cycle of stars while making it easier to collect detailed data with a simpler data collection technique.

3 Methods and Tools

To collect the data, we use the electronic 8 inch robotic telescope on the roof of the Eyring science center. It is programmed every night data is being taken to capture photos of Cygnus X-1 using the hydrogen narrow and the hydrogen wide filters along with zeros, darks, and flats. The last three of these photos are taken to subtract out the miscellaneous, unwanted information in the photos such as the dark current of the ccd, cosmic rays, and dust on the telescope. Hydrogen wide and narrow filters let in a wider or narrower band of a certain part of the spectra. In this case the filters are gathering light from the hydrogen emission spectrum. All of these photos are then run through the data reduction software IRAF, in which I combine and apply all of the photos to each other keeping the wides and narrows separate. Then, using the package “apphot” and the command “phot”, IRAF will determine the magnitude of the stars in the image. Using Equation 1 we can then determine the H-alpha value of the star.

Data collection of X Perseus will commence as it continues to get higher in the sky in a couple months.

3.1 H-Alpha Index

Hydrogen is the most abundant chemical in the universe. Due to the fact that it can be found almost everywhere, it is a suitable element to study. Particularly, I focused on the hydrogen alpha line from the Balmer series. This line is a red line in hydrogen’s spectrum and runs at a wavelength of 656 nm. The Hα index is a way to tell the temperature of the star. This is because the temperature of the star dictates how much hydrogen is at the right energy level to have the Hα transitions. Due to this, each spectral classification of stars, from hottest to coldest, O, B, A, F, G, K, M, has
Figure 2: Graph of the average Hα value versus the average temperature of the spectral classifications of stars. The spectral classification indicated by each point reads from left to right: M, K, G, F, A, B, O.

a different average Hα value (see Figure 2). Figure 2 is for absorption type stars, meaning the hydrogen electron jumps from the second valence shell to the third, absorbing a Hα photon and energy in the process. However, the two systems I am researching have emission lines. Physically, the electron in the hydrogen atom falls from the third valence shell to the second, expelling a Hα photon. When the system is more active we see a change in the Hα value, whether that be lower or higher than the mean Hα value. This mean value will be much lower than those shown in Figure 2 because those values are for absorption stars and not for emission.

Getting the Hα index from spectroscopic data is much simpler than photometric data, as IRAF has the command ‘doslit’ which will measure the width of the Hα line in the spectra. In order to determine the Hα value from photometric data we have to take pictures of the same system using both the hydrogen wide and hydrogen narrow filters. I then reduce the photos using IRAF and run the photos through ‘phot’ which determines the magnitude of the stars targeted. By analyzing the narrow and wide photos individually and then applying Equation 1 to the magnitudes, $H_N$ for the magnitude of the narrow filter and $H_W$ for the wide, we can determine the Hα value.

$$H_\alpha = H_N - H_W$$

I then plot the Hα value against time to watch how it changes for the two variable objects studied. Any variation in the value indicates activity in the star.

3.2 Calibration of Standard Stars

Inside the field of Cygnus X-1 are many other stars that may be used for the differential photometry of the variable Cygnus X-1 (Figure 3). This means that I can find the difference in magnitude between the stars that are known to have constant magnitude and the Cygnus X-1 which has changing
magnitude. Through this technique, astronomers ensure that the apparent magnitude change being measured is a true change in magnitude of the variable star. Determining the H\(\alpha\) values of the 10 stars in the same field as Cygnus X-1 eliminates the need to slew the telescope outside of the field of target variable system, saving lots of time which can be used to gather more data on the target variable. I used the data taken on the night of June 30 as the standard for all of the calibrations since that night was the clearest.

The individual H\(\alpha\) values were determined by comparing the magnitudes of the stars through the narrow and wide filters on two different nights: June 30, 2017, and July 6, 2017. The night of June 30 was a clear night during which we had data of previously calibrated standard stars in different fields (external standard stars as they were external the field of Cygnus X-1). I was able to calibrate the June 30 data by graphing the known H\(\alpha\) values (Joner & Hintz 2015) for each of the three standard stars against the H\(\alpha\) values of the same stars I calculated from the night of June 30. From this I developed the linear equation \(y = 1.04883x + 0.527271\). When this equation is later applied to other H\(\alpha\) values, it should correct the values for any discrepancies due to clouds, extra moonlight, or just a bad photo. Setting that equation aside, the next step was to find the difference in the narrow and wide magnitudes from the clear night (June 30) and the cloudy night (July 6) then subtract the offset in order to eliminate the extra light from the clouds. That newly defined value was then plugged into the slope equation as the x value. The resulting y-value should be the correct H\(\alpha\) values for the internal frame 10 standard stars.

In order to use the stars to determine the calibrated H\(\alpha\) values of Cygnus X-1, I first have to correct the recorded magnitudes through the wide and narrow filters. This is done by determining the slope and intercept (finding the linear line equation) of the 10 individual standard star averages against their measured values. This yields many resulting slopes and intercepts as there is one for each frame and the narrow and wide frames are done separately. Each slope and intercept is then applied to all ten individual star magnitudes in each respective frame. The resulting value is the corrected narrow or wide magnitude. To calibrate the next night, July 6, I did the same steps but instead of using the average value of the measured June 30 values, I used the average of the calibrated values. Similarly, for the night of data after that, July 27, I compared the measured magnitudes against the average of calibrated values from the nights June 30 and July 6. This same process was applied to the values for Cygnus X-1 at the same time, thus using the values of the standard stars in the frame to calculate the values for the variable star.

4 Results

4.1 Calibration of Standard Stars

The H\(\alpha\) values of the standard stars are shown in Table 1. The stars have been assigned a numerical value that can be matched with the stars in Figure 3 for their identification.

With the previously described technique we can use the internal 10 stars to calibrate the narrow and wide magnitudes and thus the H\(\alpha\) value for Cygnus X-1. From the June 30 night I was able to find an average H\(\alpha\) of 2.5527953, very closely matching the average H\(\alpha\) calculated using the 3 external standard stars, 2.5572.

During further investigation I found that our standard star 1 is a microvariable and a double star (Goranskuj et al. 1999), therefore removing it from our internal field standard stars list. Two other stars to possibly exclude from the standard stars list include 7 and 8. Star 7 has a very low H\(\alpha\) value which is attributed to emission objects (Figure 5). An emission line object is not the same as a standard star so I can not use it as a standard. Star 8 is believed to be a variable star. This conclusion was made after looking at its activity graph (Figure 4) and can not be said in complete certainty. For the activity graph of stars 7 and 8, I averaged the H\(\alpha\) values taken on each night to get four collective values, one for each night. This technique also helps to remove the outlying H\(\alpha\) values and makes the possible trend easier to see.
Table 1: Hα Value and Star Identifiers of Standard Stars in V1357 Cyg Field

<table>
<thead>
<tr>
<th>Star Number</th>
<th>Hα Value</th>
<th>Star Name</th>
<th>V Magnitude</th>
<th>Spectral Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.720314</td>
<td>V1674 Cyg</td>
<td>10.07</td>
<td>Microvariable</td>
</tr>
<tr>
<td>2</td>
<td>2.856972</td>
<td>HD 226867</td>
<td>10.7</td>
<td>A5</td>
</tr>
<tr>
<td>3</td>
<td>2.667624</td>
<td>HD 226918</td>
<td>9.65</td>
<td>G7</td>
</tr>
<tr>
<td>4</td>
<td>2.805494</td>
<td>Tyc 2678-137-1</td>
<td>11.56</td>
<td>F</td>
</tr>
<tr>
<td>5</td>
<td>2.916196</td>
<td>HD 226938</td>
<td>10.14</td>
<td>A0</td>
</tr>
<tr>
<td>6</td>
<td>2.856595</td>
<td>HD 226919</td>
<td>9.56</td>
<td>A5</td>
</tr>
<tr>
<td>7</td>
<td>2.535912</td>
<td>HD 189434</td>
<td>8.87</td>
<td>Emission? or A0</td>
</tr>
<tr>
<td>8</td>
<td>2.788051</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>9</td>
<td>2.829219</td>
<td>Tyc 2678-2438-1</td>
<td>11.27</td>
<td>B</td>
</tr>
<tr>
<td>10</td>
<td>2.666298</td>
<td>?</td>
<td>?</td>
<td>G8</td>
</tr>
</tbody>
</table>

Figure 3: Each of the 10 standard stars in the field of Cygnus X-1 (directly above 1) studied marked with numbers for easier identification.
In Figure 4, the activity of star 8, there is an initial definite drop in the $H_N$ magnitude and then the $H_N$ magnitude stays low. The last point drops sharply again; however, that night was very cloudy so I looked at that last data point with much more uncertainty than the others. Due to this, I can not say with certainty that the trend continues down in the manner indicated by the last data point. Upon further investigation, I found several possibly candidates to be star 8 including GSC 2678:86 and GSC 2678:158. If star 8 is the later of the two possible candidates, then it may be 3 stars imposed on one another so the changing $H\alpha$ may be different values for the different stars. I will continue investigating all of the possibilities with the hope of identifying star 8.

Figure 5, activity plot of star 7, shows a pattern very similar to that of the trough of a sine wave. Even though this trend looks very promising, further research into the surrounding stars has led me to believe that star 7 is HD 189434, a standard star. This later conclusion contradicts the data so further investigation to the true nature of this star will be necessary.

As I continue to get data on Cygnus X-1, I will be able to further analyze the behavior of these two stars. The final goal is to successfully identify periodic activity and completely take these stars off the list of 10 internal standard stars.

**4.2 Cygnus X-1**

Figure 6 shows a graph of activity of Cygnus X-1. There are many gaps in the data taken as the time span is 7 years but a pattern of changing $H\alpha$ values is still apparent. We know the period of Cygnus X-1 is 206 days, so with the large span of the x-axis I only expect to see clustered variation in the data on the plot. This is what we can see when looking at the activity plot of Cygnus X-1, so it is warranted to say that the $H\alpha$ calibration is properly showing the changing activity of the HMXB.

A majority of the data points shown in the Cygnus X-1 (or V1357 Cyg) activity graph were
analyzed from spectroscopic data. The last line of data points on the far right were calculated using differential photometry. Each of the points represents the average of a set of data taken on four different nights. The highest point and the second lowest were taken on cloudy nights so there is much more uncertainty in those two points than the other two which were taken on pretty clear nights. Due to this these points do still follow the trend of data staying towards the second highest point. This point is an average of points taken on the very clear night of June 30. When comparing this point to the same data calculated using the three external standard stars, it is the same until the third decimal point. The bottom point was data from July 6, a cloudier night, that was corrected and then calculated using the 10 internal standard stars. It is a little low but still indicates higher activity just as the point from June 30 does.

In addition to the long term data trend, I attempted to make a short term plot of activity for Cygnus X-1. Although I tried many times to recover the data, it was too cloudy that night to produce data that I trust. More observations over short periods will be needed to continue to study the short term activity.

4.3 X Perseus

All of the data analyzed for X Perseus was spectroscopic data taken at the Dominion Astrophysical Observatory (DAO). The graph of H$\alpha$ value versus the Julian date is shows in Figure 7. I analyzed the data using IRAF as described earlier and plotted the resulting figures.

It is very easy to see the sinusoidal pattern in the plot.

4.4 Photometry to Spectroscopy

Figure 6, the plot of Cygnus X-1 activity, is a merge of both spectroscopic and photometric data. Without being told which data points were which technique, it would be difficult to differentiate
Figure 6: Activity graph of the HMXB Cygnus X-1 showing Hα value versus Julian date.

Figure 7: Activity graph of HMXB X Perseus showing Hα value versus Julian date.
between the two. The data points on the far right edge were all calculated using differential photometry. Despite the large gaps in the data there is still an apparent pattern of activity even if that pattern is more chaotic than a sine wave.

5 Conclusions

The sinusoidal patterns of the Cygnus X-1 and X Perseus indicate activity of the two HMXB. Any deviation of the Hα value from their mean represents a higher activity. This is because the Hα is measuring the amount of hydrogen at the right temperature to have the alpha transitions, so a shifting amount of hydrogen in that energy level means a shifting temperature of the star and thus activity.

Seamless flow of Hα values to show activity means the transition of data from photometric observations to spectroscopic analysis works. The data points in Figure 6 around 2.458×10⁶ were determined using differential photometry and still continue the trend of broken activity. I was able to calculate these values using both the internal frame 10 standard stars and the external frame 3 standard stars. These two techniques yielded very similar results.

I will continue to analyze data on both Cygnus X-1 and X Perseus over the next couple of months. More observations of these objects will continue after the REU period since X Perseus will be visible and in a good target range in the Fall. This data will be added to the activity graph as to monitor both systems. It will also be analyzed using differential photometry, further supporting our conclusions of the seamless interaction between spectroscopy and photometry with the Hα index.

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7 Bibliography


