H-alpha and H-beta Variations in X Persei and Gamma Cassiopeiae

Tyler Harding

A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science

Eric Hintz, Advisor

Department of Physics and Astronomy

Brigham Young University

April 2022

ABSTRACT

H-alpha and H-beta Variations in X Persei and Gamma Cassiopeiae

Tyler Harding
Department of Physics and Astronomy, BYU
Bachelor of Science

We observed X Persei and Gamma Cassiopeiae from 2010 through 2020 using the Dominion Astrophysical Observatory. These observations were taken to monitor the systems over time and discover any new changes. We applied the method described in Joner 2015 to obtain a measurement of the H_α and H_β emission line strength. We plotted and analyzed variations in these measurements over time. The H_α and H_β measurements were then compared to the V magnitude to identify similarities or differences within the time series. We found that X Persei had an odd correlation with the V magnitude and had a significant drop in brightness at about JD 245800. Gamma Cassiopeiae did not have any periodicity in H_α, H_β, or V magnitude measurements.

Keywords: H-alpha, H-beta, emission lines, X Persei, Gamma Cassiopeiae, X-ray binary

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Hintz, for guiding me in this project. This project would not have been possible without his help. I also thank Brigham Young University, especially the Physics and Astronomy department, for providing funding and teaching all the concepts necessary to work on this project. I would like to acknowledge the AAVSO for providing critical data in this study. I also recognize DAO for providing years of data that made this project possible. I also thank family and friends, especially my wife, who provided support while taking time work on this project. I thank the Christa McAuliffe Space Center for inspiring me to study things out of this world.

Some/all of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NNX13AC07G and by other grants and contracts.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Our study examines two stellar systems: X Persei and γ Cassiopeiae. These systems have at one point been classified as High Mass X-ray Binary systems, which provided an interesting source for information about High Mass X-ray Binary systems in general. Our focus was on the periodicity of X Persei and γ Cassiopeiae, from which physical attributes such as the mass of the stars and the semi-major axis of the orbit could be determined. Our goal was also to monitor variations in the systems over time and discover any new changes. Changes in the periodicity could provide insight to changes in mass and orbital distance over time in High Mass X-ray Binary systems.

1.1 X-ray Binaries

To understand the basics of our study, a background of High Mass X-ray Binary (HMXB) systems is necessary. A HMXB system contains two stellar objects. One is a large O or A type star while the other is a compact object such as a white dwarf, neutron star, or black hole. The compact object is much less massive than the large star, so it orbits the large star. Large stars, especially O and A stars, shed some of the gases from their outer layers as they evolve over time. As the compact object moves through the gas shed by the large star, the gas falls quickly onto its surface. The gas moves faster and faster as it approaches the compact object's surface, eventually reaching relativistic speeds. The gas reaching these speeds is what releases X-rays, thus providing the name X-ray binary.

The knowledge from studying HMXB systems is applicable to other aspects of astronomy, not only to the systems themselves. HMXB systems contain a large star, making them rare when compared to other systems. More observations of these HMXB systems can improve our knowledge of them and what we can expect other HMXB systems to behave like. We also gain insight on how stars evolve over time from observing HMXBs. With the compact object as part of the binary couple, we can learn how compact objects behave in general.

HMXBs also provide insight to areas of relativity and gravity. The large star in the HMXB system will end its life as a neutron star or a black hole– another compact object. This leads to orbiting and merging neutron stars or black holes. Systems of merging black holes and neutron stars are the focus of study for gravitational waves (Rizzuto et al. 2022). Better understanding the predecessor of these systems can give better insight to these areas of study.

1.2 X Persei

X Persei (X Per) is a known HMXB system that has been studied by many astronomers throughout the years. From their observations, the recorded V magnitude of X Per is listed as 6.7 (Oja 1991) and the orbital period of the compact object around the large or parent star has been measured to be about 250 days (Delgado-Martí et al. 2001). Figure 1.1 shows an image of X Per and its surrounding field. Our observations of X Per add to the observations taken by others, but also focus on any changes that happened in the system during the time of the study.

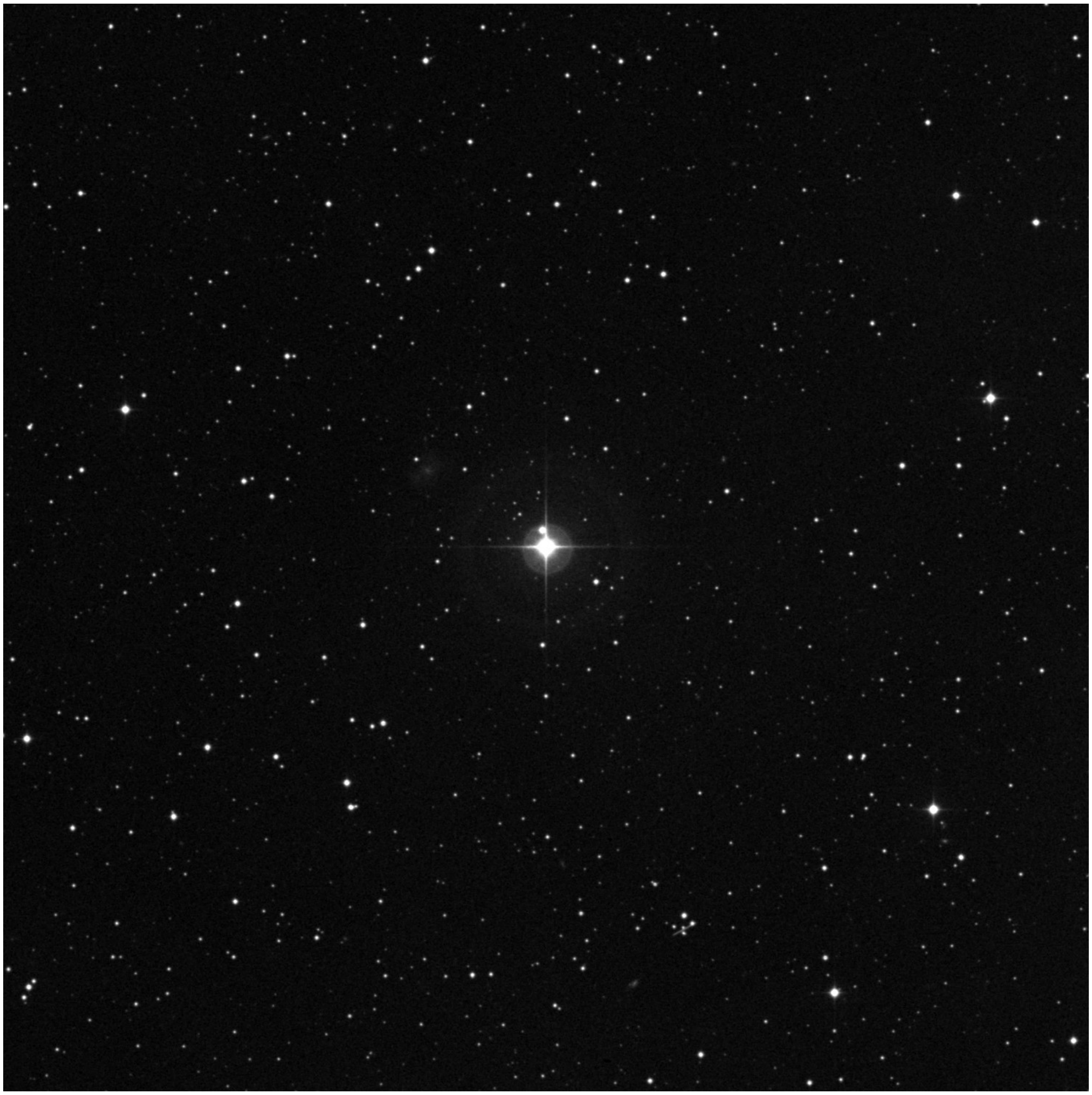

Figure 1.1 An optical image of X Per. The bright star at the center of the frame is X Per. As noted, HMXBs are O and A stars which are very hot and bright. This is why X Per is much brighter than any other star in the frame.

1.3 γ Cassiopeiae

γ Cassiopeiae (γ Cas) is a star that has been previously identified as a HMXB, but recent studies question this claim. This uncertainty makes γ Cas ideal for further study. γ Cas is currently identified as a Be type star. The orbital of the period was originally identified to be about 203 days (Harmanec et al. 2000), but this is disputed in other papers (Robinson et al. 2002). The average V magnitude has been recorded as 2.39 (Ducati 2002). Figure 1.2 shows an image of γ Cas and its surrounding field. By observing γ Cas we hoped to show whether the star should be identified as an HMXB or not, in addition to providing more data points for the use of others.

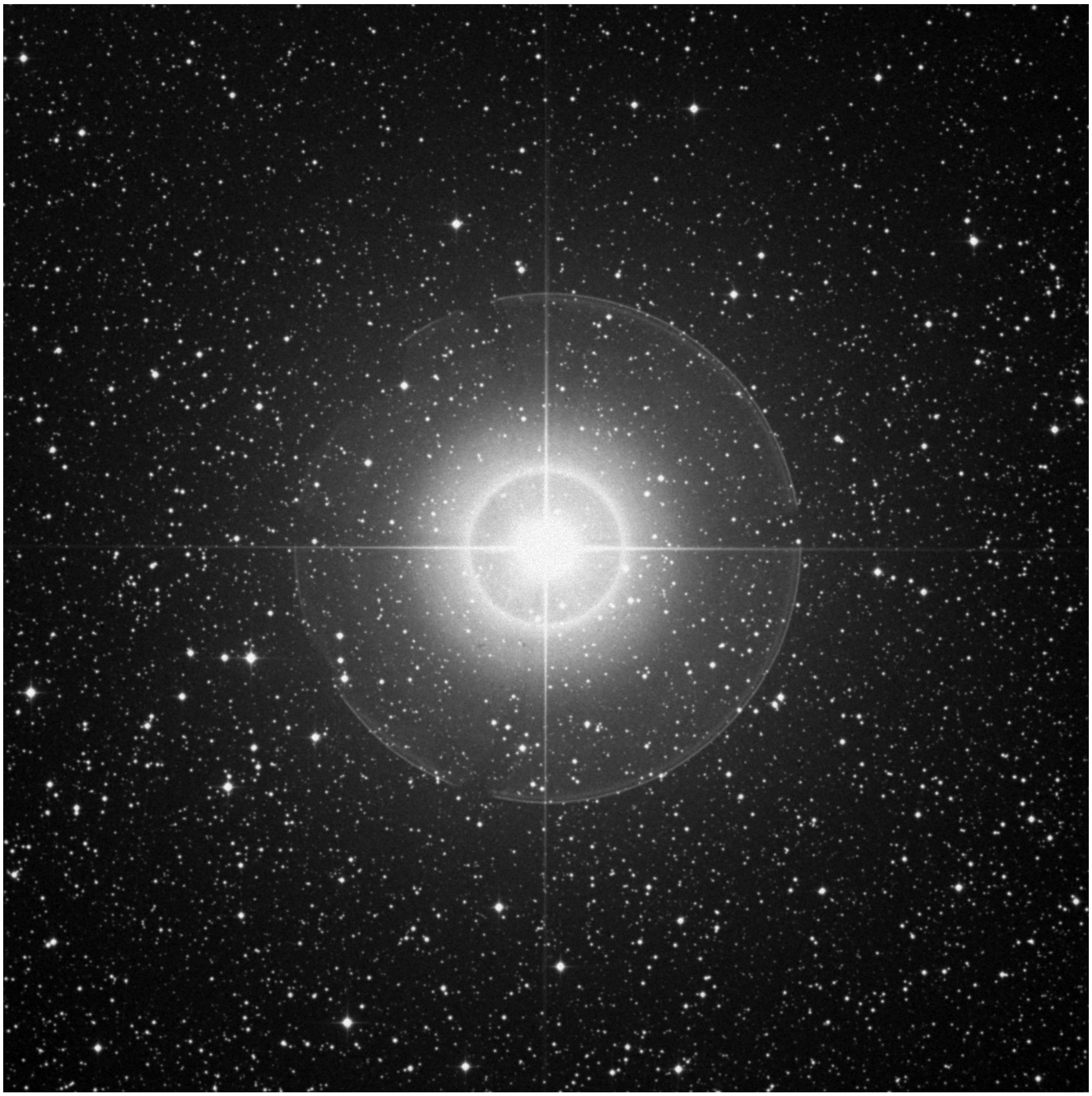

Figure 1.2 An optical image of γ Cas. The very bright star at the center of the frame is γ Cas. As noted, HMXBs are O and A stars which are very hot and bright. This is why γ Cas is much brighter than any other star in the frame.

Chapter 2

Methods

By studying the systems of X Per and γ Cas we hoped to gain more knowledge of how these systems evolve over time. The process for this study consisted of three main areas: gathering the data from observations, gathering data from archival sources, and the analysis of the data. From the analysis we were able to highlight areas where significant changes in the systems occurred and determine some physical implications of X Per and γ Cas.

2.1 Observations

Our spectroscopic data was collected using the 1.2 meter McKellar Telescope of the Dominion Astrophysical Observatory (DAO). The observations of X Per were collected starting in 2010 and ending in 2020, and 66 nights of data were collected during that time. We took observations of γ Cas 87 nights from the years 2011 to 2020. The spectroscopic measurements were taken using the Coude spectrograph with a 3231 grating.

The Coude spectrograph is an instrument the size of a room, where the light collected from the telescope is received. The light is spread so the intensities at different wavelengths can be analyzed. We used a 3231 grating which spread the light apart. This grating provided 40.9 $\text{Å}\,\text{mm}^{-1}$.

Also part of the setup was a Site4 CCD with 15 μm pixels that resulted in 0.614 Åpixel^{-1}. This refers to how much of the collected light is represented on each pixel. With 4096 pixels along the dispersion axis we obtained a total coverage of about 2500 Å. This grating was aligned with a central wavelength of 5710 Å, thus covering wavelengths from 4450 to 6970 Å. The selected range allowed for measurements of H_α and H_β emission lines.

2.2 Archival Data

For comparison purposes, visual data was needed in addition to the spectroscopic data. This was gathered using measurements submitted to the American Association of Variable Star Observers (hereafter AAVSO) website. The AAVSO has members around the country that record data on various stars and publish it for public use (Kafka 2021). From their data archives, the needed visual magnitudes of X Per and γ Cas were obtained. The AAVSO provided 139 data points for X Per for the years 2010 through 2020. For γ Cas, 584 data points were also provided during the years 2011 through 2020.

2.3 Analysis

After collecting our data sets, reduction of noise was needed to complete the analysis. The photometric data from AAVSO had already been reduced, but data gathered at DAO needed to be reduced of possible errors and noise. To achieve this, we used software packages available through IRAF and removed background noise from the spectra. Figures 2.1 and 2.2 show what a typical spectra of X Per and γ Cas looked like before reduction respectively. A noticeable feature in the figures is a general upward trend in the data as the wavelength increases. This is a result of background noise that was removed through reduction. The prominent element in figure 2.1 and 2.2 are the large spikes at approximately 4900 Å and 6500 Å. These features are the H_β and H_α

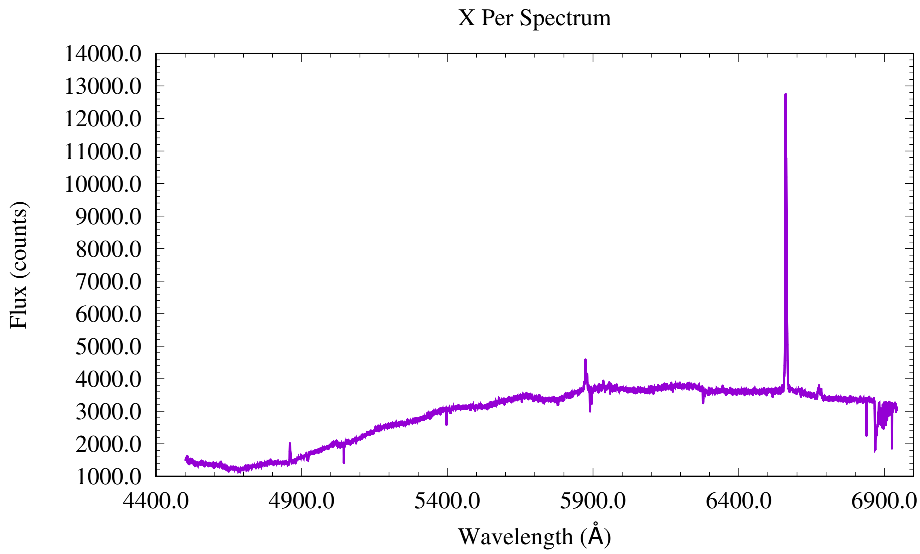

Figure 2.1 Typical data for X Per collected from DAO before processing. The spike near 4900 Å is the H_β emission line and the spike near 6500 Å is the H_α emission line. The upward trend of the plot from left to right shows the background noise of the spectrum.

emission lines respectively. Figures 2.3 and 2.4 are a close view of just the H_α emission line. In figure 2.3 a break in the peak of the emission line is a result of the Doppler shift. The Doppler shift is a result of the compact object moving around the parent star. We also used IRAF to make an initial measurement of the equivalent width of the H_α and H_β lines.

Over the years, several methods of creating a categorized index for different types of stars have been postulated. Most notably are the four color index and H_β photometry. Joner and Hintz propose a standardized index using H_α measurements in their 2015 paper (Joner & Hintz 2015). Because HMXBs are usually connected with O and A stars, the H_α line is the dominating feature in their spectrum. Because of this, we chose to use the Joner 2015 H_α and H_β index to standardize our observations. This index is the difference of two filters, the wide and narrow filters. After finding the difference, the value was then adjusted relative to a zero-point determined from several standard stars. Table 2.1 shows the comparison between the measured equivalent width of various stars and their calculated H_α and H_β index as described in Joner 2015. Using this method the collected

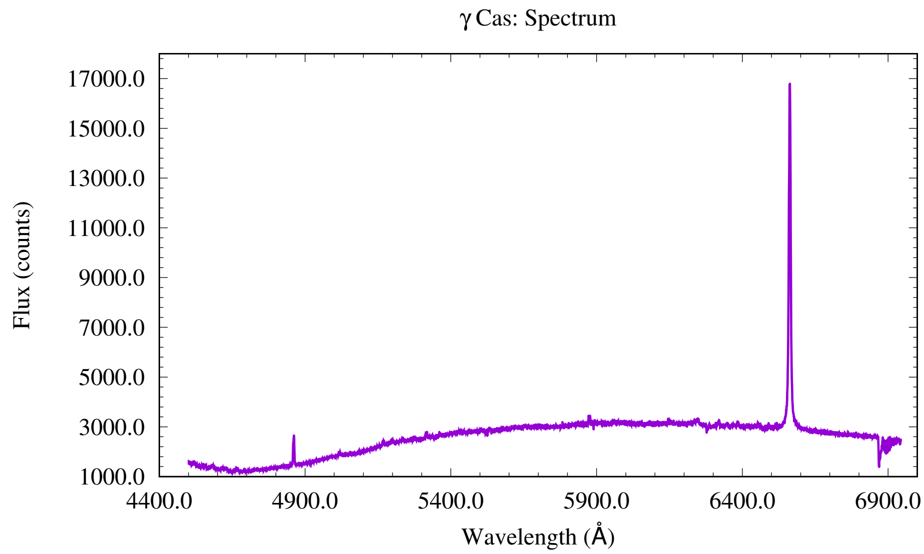

Figure 2.2 Typical data for γ Cas collected from DAO before processing. The spike near 4900Åis the H_β emission line and the spike near 6500Åis the H_α emission line. The upward trend of the plot from left to right shows the background noise of the spectrum.

spectra were converted to their H_β and H_α indices (hereafter H_β and H_α). We then created plots showing how H_β and H_α varied over time for both X Per and γ Cas. The data sets were then analyzed for patterns and anomalies.

After gathering the visual data from archival sources, it was organized into filters using spreadsheet software. Similar to how the H_α and H_β measurements were plotted, the magnitudes of X Per and γ Cas were plotted over time. We found that the errors in the observed magnitudes were negligible in both X Per and γ Cas. These plots were then matched with their respective plots of H_α and H_β to see if the spectroscopic data had any significant correspondence with the visual data.

Using the data and plots of both the spectroscopic and visual data, the time series of both X Per and γ Cas were processed using Period04 and Peranzo software. This software uses Fourier analysis to identify periodicity in a given time series. We analyzed possible orbital periods of the objects and compared the timing against other sources.

Table 2.1. H_α and H_β versus Equivalent Width Values for Emission Line Targets

Object	H_α	Eq. Width nm	H_β	Eq. Width nm
kap Dra	2.165	-1.582	2.586	0.232
1H 1936+541	1.995	-2.381	2.493	-0.238
V1357 Cyg	2.549	-0.051	2.554	0.112
lam Cep	2.538	-0.014	2.545	0.125
AG Dra	1.737	-3.948	2.191	-1.395
1H 2202+501	1.770	-3.886	2.532	0.032
4U 2206+54	2.525	-0.076	2.552	0.112
52 Aql	2.405	-0.605	2.520	0.066
alf Cam	2.496	-0.229	2.524	0.084
HD 229221	1.934	-2.786	2.424	-0.303
HD 283447	2.526	-0.446	2.527	-0.028
X Per	1.953	-2.693	2.400	-0.382
HD 31293	2.077	-2.143	2.780	1.403
RX J0440.9+4431	2.267	-1.108	2.480	-0.122
EXO 051910+3737.7	1.902	-3.054	2.414	-0.304
1A 0535+262	2.216	-1.248	2.456	-0.193
4U 0548+29	1.828	-3.377	2.466	-0.248

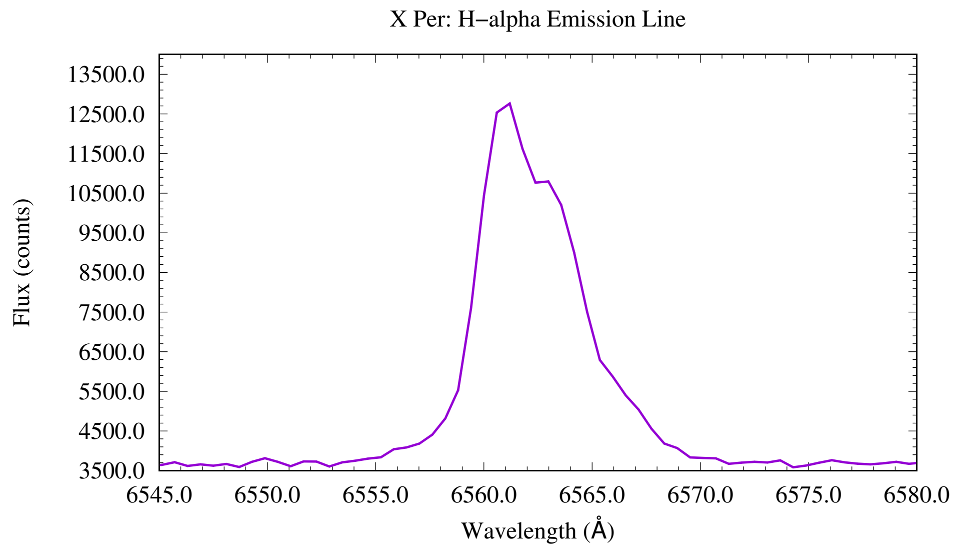

Figure 2.3 A zoomed in view of the H_α emission line in X Per. The break at the peak is a result of the Doppler shift as the compact object moves around the parent star.

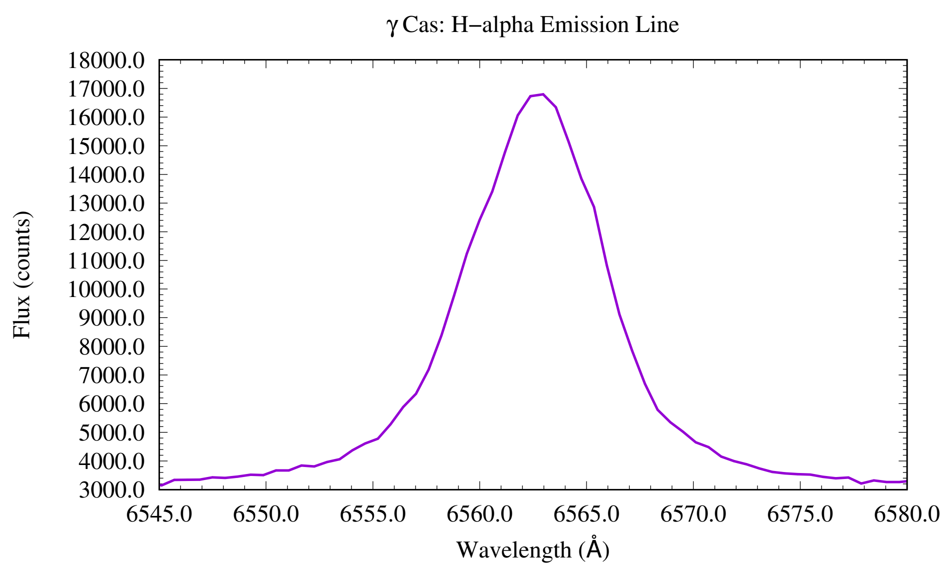

Figure 2.4 A zoomed in view of the H_α emission line in γ Cas.

Chapter 3

Results

This chapter will focus on the results of the observations and comparisons made for both X Per and γ Cas. For each star the spectroscopic and visual observations will be addressed first, and then the analysis of the data sets will be discussed. Finally, this chapter will include a review of significant findings in X Per and γ Cas and give ideas for further research on these objects.

3.1 X Persei

3.1.1 Spectroscopic Results

The results of the spectroscopic measurements provided new insight to X Per. A plot of the H_α values are shown in figure 3.1. The points on the graph with lower values represent when the object has a stronger H_α line. One can clearly see that some activity is happening in the system of X Per, but attempting to fit the data to a periodic function with the software mentioned above did not produce any results. Although the period could not be determined in this way, many significant insights can be made into attributes of the system from the H_α values.

The H_β measurements reflected many of the same results. A plot of the H_β values are shown in

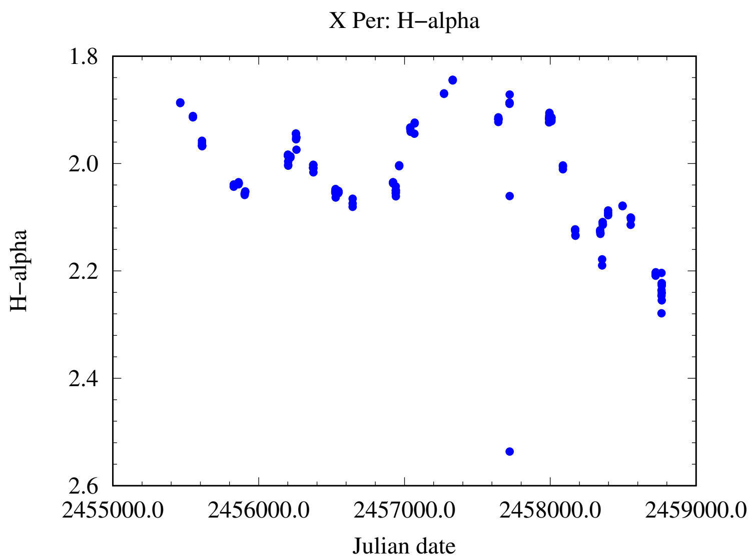

Figure 3.1 Data points collected from 2010 to 2020. The y-axis shows the calculated H_α strength over time. The figure shows no exact periodicity, but the variation in the system cannot be ignored. A true X-ray binary system would show sinusoidal variation over time, whereas the H_α strength in X Per begins to fall out of this motion around JD 2458000.

figure 3.2. In O and A stars the H_β emission line is smaller and weaker than the H_α line. We see this trend in figure 3.2. The same general features in the H_α plot can be seen in the H_β plot, but there is more scatter in H_β. This result led us to use the H_α values for our comparisons and not H_β.

3.1.2 Visual Results

As expected for HMXBs, the spectroscopic data had many similarities to the photometric. Figure 3.3 shows data collected in the V filter during the same years that the spectroscopic observations were taken. The magnitude of X Per (listed on the y-axis of figure 3.3) varied in a semi-periodic fashion over time. Because the data points are semi-periodic, a period was not obtained from the visual data. Although H_α is varying over time, a significant drop-off in brightness is seen at about JD 2457000. Due to the timing in our observations we do not know if the H_α index rose again to its previous strength.

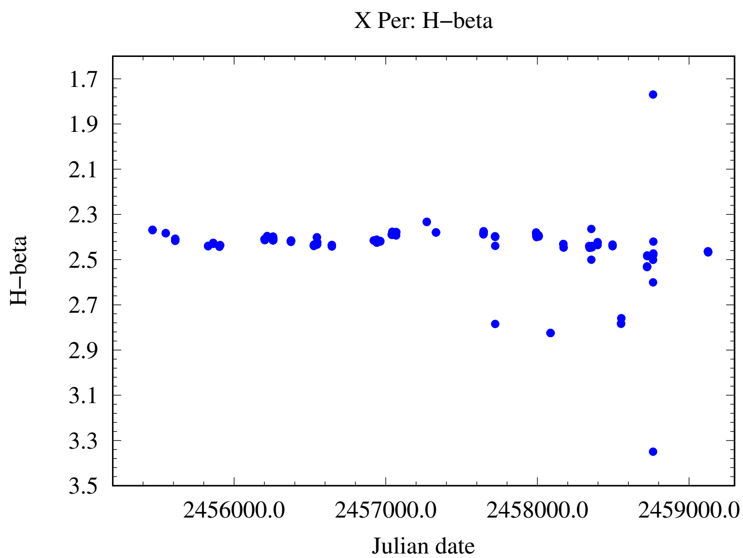

Figure 3.2 The H_β strength plotted over time. The plot has the same general trends as the H_α values, but there is more scatter in the data. This is a result of the H_β emission line being weaker than the H_α line.

3.1.3 Comparison

By comparing the spectroscopic and visual data many similarities can be seen. Figure 3.4 shows the H_α and the visual data sets compared on top of one another. One of the main similarities is the peaks in the data sets happen on almost the same dates. This shows that events happening spectroscopically are also happening in the visual spectrum at other wavelengths. For an ideal HMXB, the peaks on the plot would correspond to when the compact object is at its nearest point in its orbit around the massive star. These peaks would also maintain a sinusoidal pattern throughout the observation time. The correlations in our data were not expected, but provide a broader sense of physical aspects of the system.

Although there are many similarities between the spectroscopic and photometric data sets, the differences are also just as insightful. Something interesting seen in the plots is that even though the peaks of the data sets line up, the trends do not match. When the H_α strength falls over time the visual magnitude increases. We cannot conclusively determine what is actually happening in the

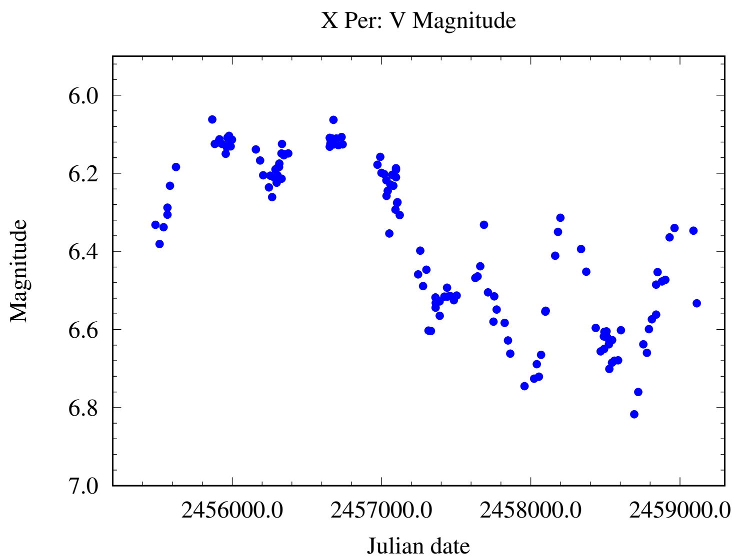

Figure 3.3 The magnitude of X Per as recorded during the years 2010 to 2020. The y-axis shows the magnitude of the star as seen in the V filter. The changes in the magnitude do not follow any simple period, but the system is evolving over time.

system to create the results we obtained, and any guess is purely speculation. Some ideas of what could cause these results range from pulsations in the parent star to an accretion disk that absorbs an array of light frequencies.

3.2 γ Cassiopeiae

3.2.1 Spectroscopic Results

The spectroscopic data for γ Cas provided a better understanding of the object. The measurements showed that while H_α varied over time, it had no periodicity. These changes are shown in figure 3.5. Significant drops in brightness happened throughout the time we observed, but the drops did not seem to follow any pattern either in timing or in their depth. An interesting event happened at about JD 2456900, where the largest drop in H_α strength occurred. This significant drop in H_α strength is unusual, and this event could potentially be the result of an eclipse in the system. Although

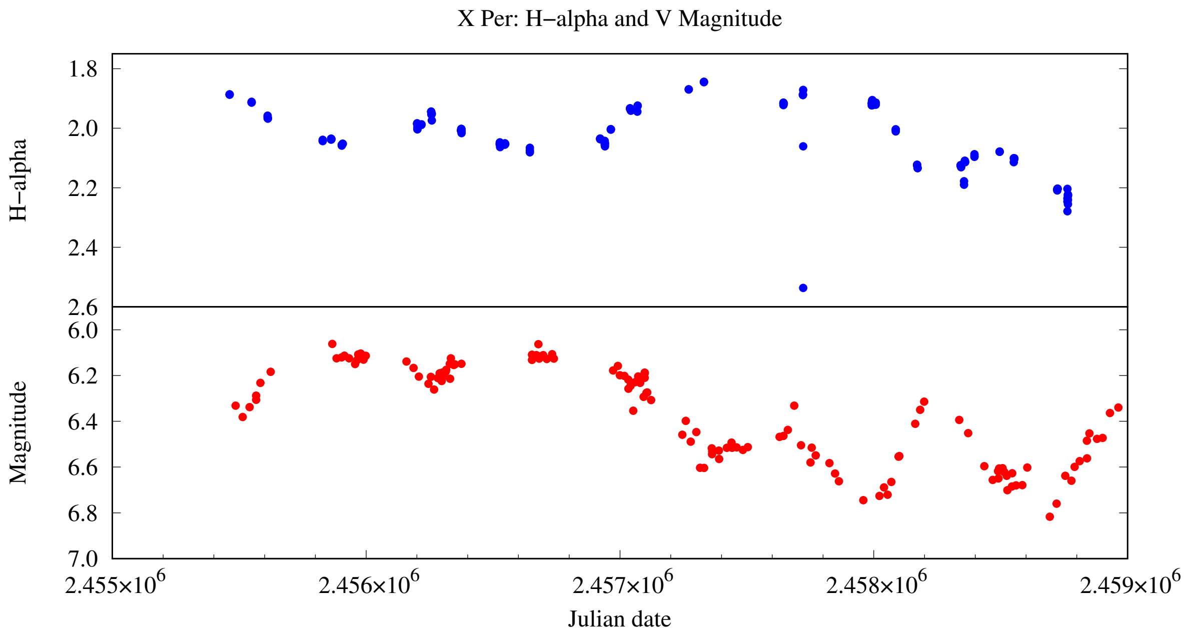

Figure 3.4 Comparison of H_α and V magnitude in X Per. Both Figure 3.1 and 3.3 are brought onto the same plot highlight their similarities and differences. The top plot shows the H_α strength versus Julian Date, and the bottom plot shows the magnitude versus the Julian Date.

the object itself is likely not an X-ray binary, it still may be a binary system. By this model, the companion star blocks the X-rays coming from the parent star as the light travels to earth.

Similar to the H_β values for X Per, the H_β values for γ Cas were weaker than H_α. Figure 3.6 shows the H_β values for γ Cas during the time observed. Because of the weakness of the H_β emission line, the H_β value appears almost constant over the observation time. A few drops in brightness occur but they do not seem correlated with the H_α values at all. This again led to a focus on the H_α values as opposed to the H_β for our analysis.

3.2.2 Visual Results

The visual data for γ Cas provided no new revelations. The magnitude of the star had some variation over time, but the variations were not significant and did not follow any sort of periodicity. The

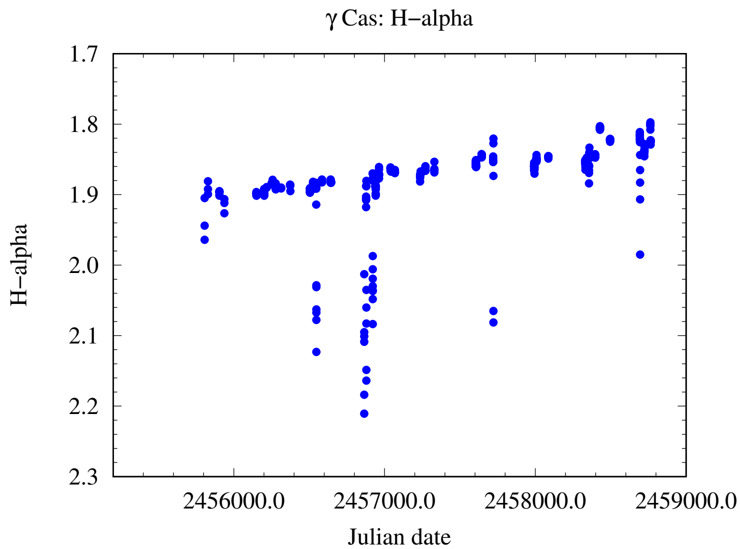

Figure 3.5 Collected data points of H_α strength of γ Cas during the years 2011 to 2020. Although the system shows no periodicity, a steady increase in the H_α is interesting. Significant drops in the strength of the H_α throughout the plot (most notably at about JD 2456900) also occur at varying times.

visual data is shown in figure 3.7. This is about normal for any given star, especially a Be type star. With no significant periodicity, no events could be identified or analyzed from the visual data.

3.2.3 Comparison

Comparing the spectroscopic and visual data showed no correlation. Figure 3.8 shows both the H_α and the visual data laid on top of one another. From simple inspection, one can see that the drops in H_α strength do not correspond to any interesting events in the visual data set. While this might seem uninteresting, this shows that events happening with H_α are not connected with other wavelengths of light.

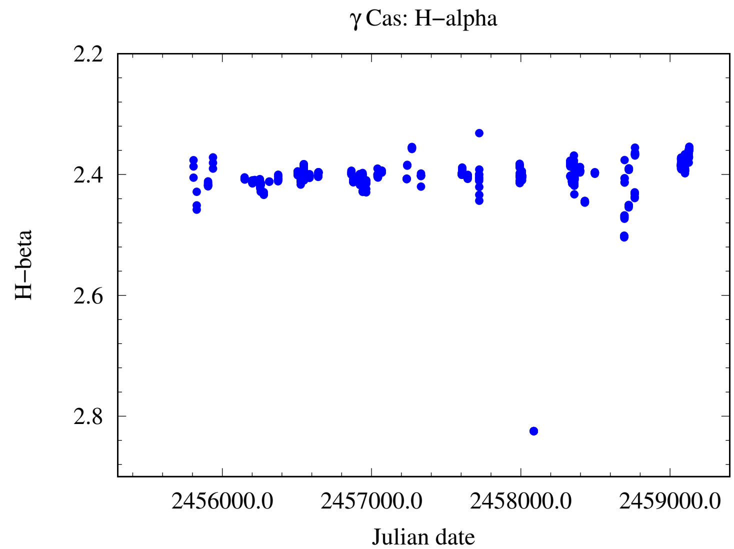

Figure 3.6 The H_β values plotted over the observation time. A slight upward trend can be seen, but the H_β value almost appears constant. A few drops in the strength can be seen, although they do not seem to correspond with the H_α values.

3.3 Conclusion

X Per and γ Cas both have interesting phenomena happening within their systems. In X Per we have observed a correlation between H_α and the V magnitude. When H_α decreases the V magnitude increases and vice versa. This interaction cannot be explained by any models of HMXBs that currently exist. Further study of this system would include creating a model to fit the correlation we have observed. In γ Cas the cause of the large drops in H_α remains uncertain. Speculations of their origin could include extreme mass loss or pulsations of the star. For a clear model of the stellar system, further observations in other filters and study are needed.

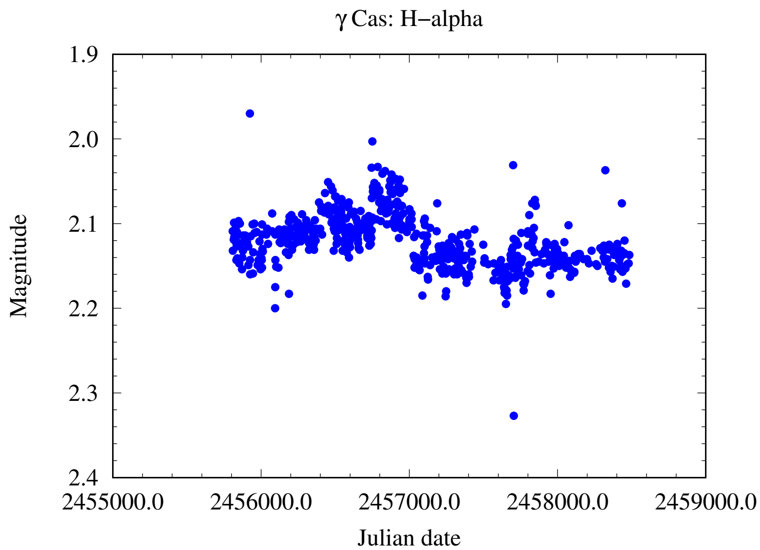

Figure 3.7 The V magnitude of γ Cas during the years 2011 through 2020 as collected. Although there appears to be some variation in the data at about JD 245700, no significant trends exist in the data.

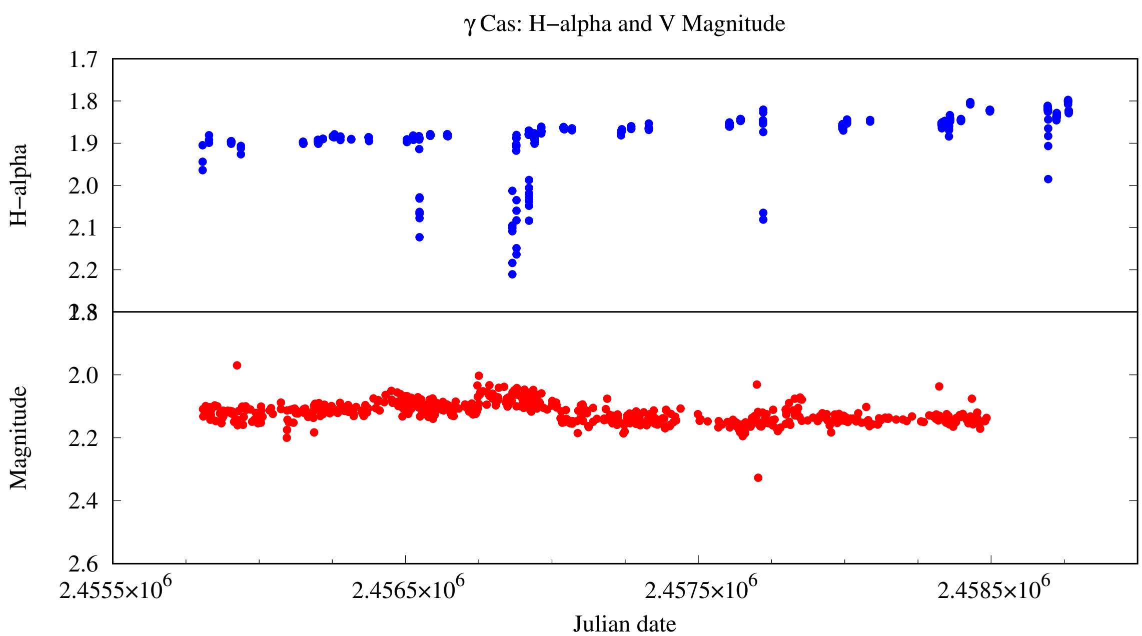

Figure 3.8 Comparison of H_α and V magnitude in γ Cas. Both figure 3.5 and 3.7 are brought on top of one another for easy comparison. The top plot shows the H α strength versus Julian date and the bottom plot shows the V magnitude versus Julian date. The V magnitude appears to be almost constant during the years of observation while significant drops occur in the H_α strength.

Bibliography

Delgado-Martí, H., Levine, A. M., Pfahl, E., & Rappaport, S. A. 2001, ApJ, 546, 455

Ducati, J. R. 2002, VizieR Online Data Catalog

Harmanec, P., et al. 2000, A&A, 364, L85

Joner, M. D., & Hintz, E. G. 2015, The Astronomical Journal, 150, 204

Kafka, S. 2021, Observations from the AAVSO International Database

Oja, T. 1991, A&AS, 89, 415

Rizzuto, F. P., Naab, T., Spurzem, R., Arca-Sedda, M., Giersz, M., Ostriker, J. P., & Banerjee, S. 2022, MNRAS, 512, 884

Robinson, R. D., Smith, M. A., & Henry, G. W. 2002, ApJ, 575, 435

Index