Stellar Models and Physical Properties of Be Stars in High Mass X-ray Binaries

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Abstract: This research focused on obtaining the physical properties of the Be stars in high mass X-ray binaries. I created and developed an IDL program to compare the observed fluxes in ultraviolet, Johnson UBV, and 2MASS JHK wavelength bands to the available stellar models from TLUSTY. By finding the flux ratio, I could find the best fit model for each Be star and extract its physical properties such as distance, radius, interstellar reddening, temperature, and mass. Each Be star is also surrounded by a circumstellar disk that produces an infrared excess and H-alpha emission. However, due to the scatter and low correlation of the data between H-alpha equivalent widths and the magnitudes of color indices E(H-K) of the Be stars, the size of circumstellar disks of the Be stars still remain undiscovered.

Introduction

I am interested in obtaining the physical properties of Be stars in high mass X-ray binaries (HMXBs). A Be star is a subtype of the spectral classification B with the effective surface temperature of 10,000 to 30,000 K, a massive blue star on the Main Sequence. A Be star demonstrates a significant difference from a normal B star, which is its emission lines of hydrogen. The emission lines are produced from a circumstellar disk surrounding the star, which originates from rapid rotation and pulsation over the surface of the star. In most HMXBs, which are close binary systems with one of the members being a neutron star or a black hole, accreting matter from a Be star is the origin of the X-ray radiation.

Physical properties of the Be stars such as distances, radii, temperatures, interstellar absorptions, masses, and size of their disks, have combined influences on their spectra. Thus, one way to untangle this problem is to fit various models, which contain as many variables as possible, and compare them to the available spectra to obtain the physical properties. Therefore, under Professor M. Virginia McSwain's guidance, I developed an IDL program to compare the observed spectra of the Be stars to the stellar models from TLUSTY with different sets of variables to obtain the best represent models and their parameters.

Method

First, I gathered the observed magnitudes and fluxes in UBV and JHK wavelength bands of the Be Stars from Catalogue of High Mass X-ray Binaries in the Galaxy (Liu et al, 2006). I also included the observed ultraviolet fluxes of the Be stars to constrain their magnitudes of interstellar reddening.

I converted the apparent magnitude in each band into apparent flux. Since the observed fluxes depend on the radius and distance of the Be stars, finding the radius of the Be star could yield the distance. Thus, I made the assumption that the Be stars in HMXBs are all on the Main Sequence. By this assumption, the Be stars should have a well defined mass-radius and mass-temperature relationships; so we could obtain the radius of a Be star specific to the effective temperature in each stellar model.

With Prof. McSwain's guidance, I developed an IDL program to take in arrays of absolute fluxes of each stellar model from the TLUSTY database of the Be stars. The program averaged the fluxes of the stellar models every 50 Å to remove absorption line structures, leaving the continuum spectra and broadband features. The program finds the ratio between the absolute model fluxes and the apparent fluxes of the stars. The program then compared the models with effective temperature from 15,000 K to 30,000 K, the interstellar reddening from 0.0 to 2.0, and the distance calculated from the radius obtained from temperature-radius relationship of Main Sequence stars and the flux ratio to find the best model that demonstrated the minimum deviation between the observed fluxes and the stellar model fluxes of the Be stars.

Since the infrared excess in the Be stars' spectra is caused by the disks, I omitted the JHK fluxes from the fitting process. The outputs of the program at this point were the magnitude of interstellar reddening, effective temperature, radius, distance, surface gravity, and flux differences in J, H, and K bands in comparison to the best fit stellar model. The program also plots the results by showing all the observed flux points on the spectral energy distribution curve from the best fit stellar model.

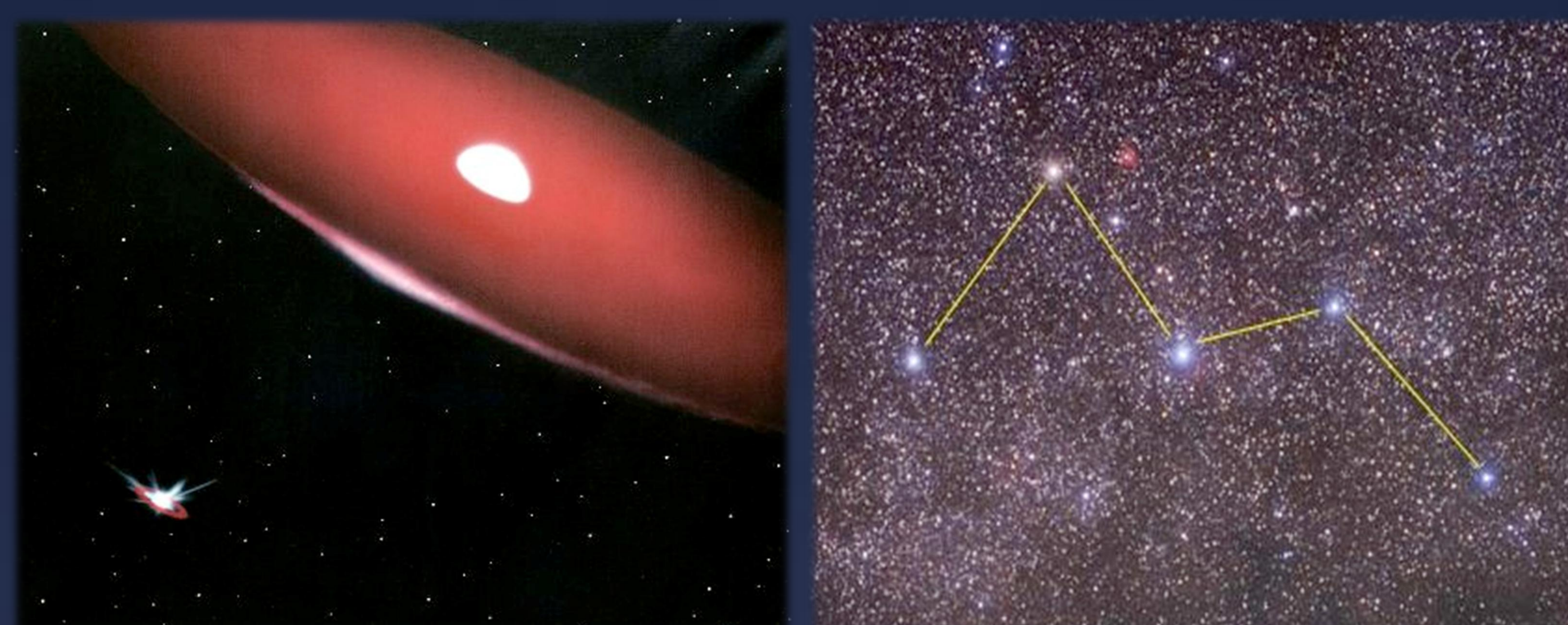

Figure 1 left : Illustration of a Be star with a circumstellar disk with a compact companion (left)
Credit: Douglas Gies (CHARA, GSU) et al. **Illustration:** William Pounds
Figure 1 right : Constellation of Cassiopeia with γ Cas in the middle of the "M" shape
Credit: verdantgryphon.com

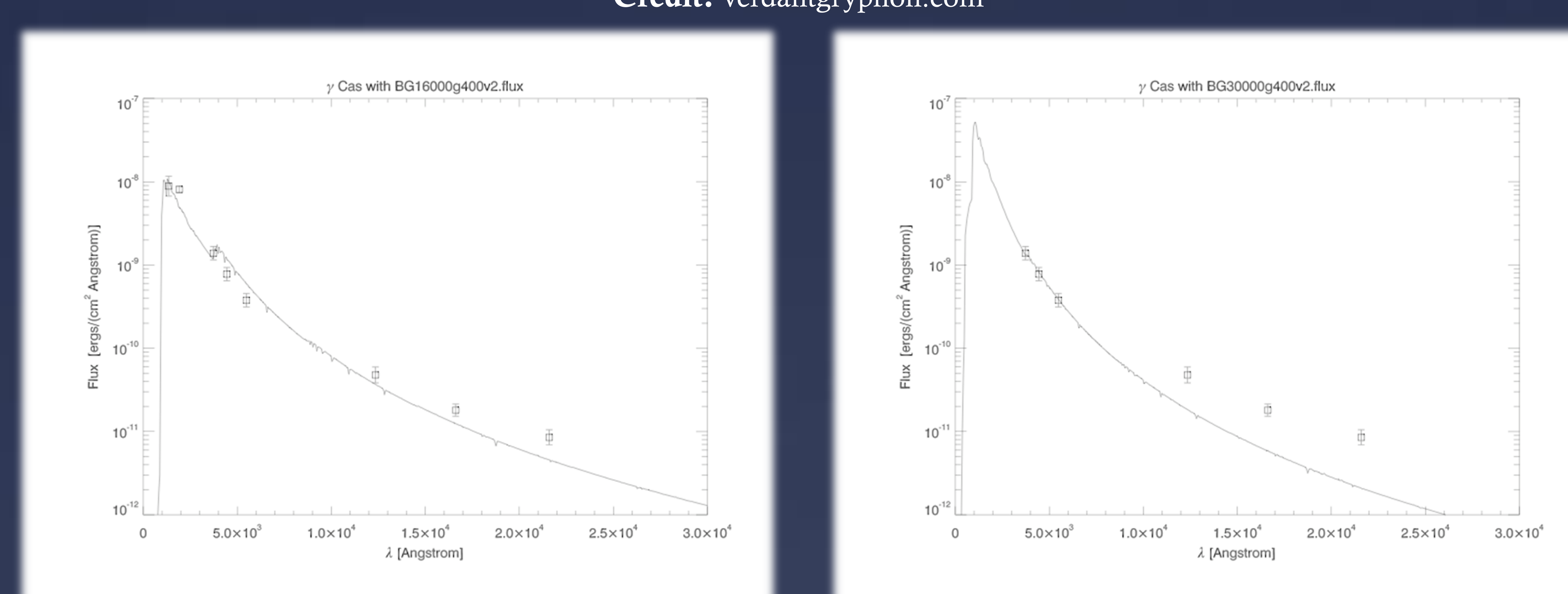

Figure 2: Observed flux points of γ Cas with the best fit stellar models with ultraviolet fluxes (left) and without ultraviolet fluxes (right)

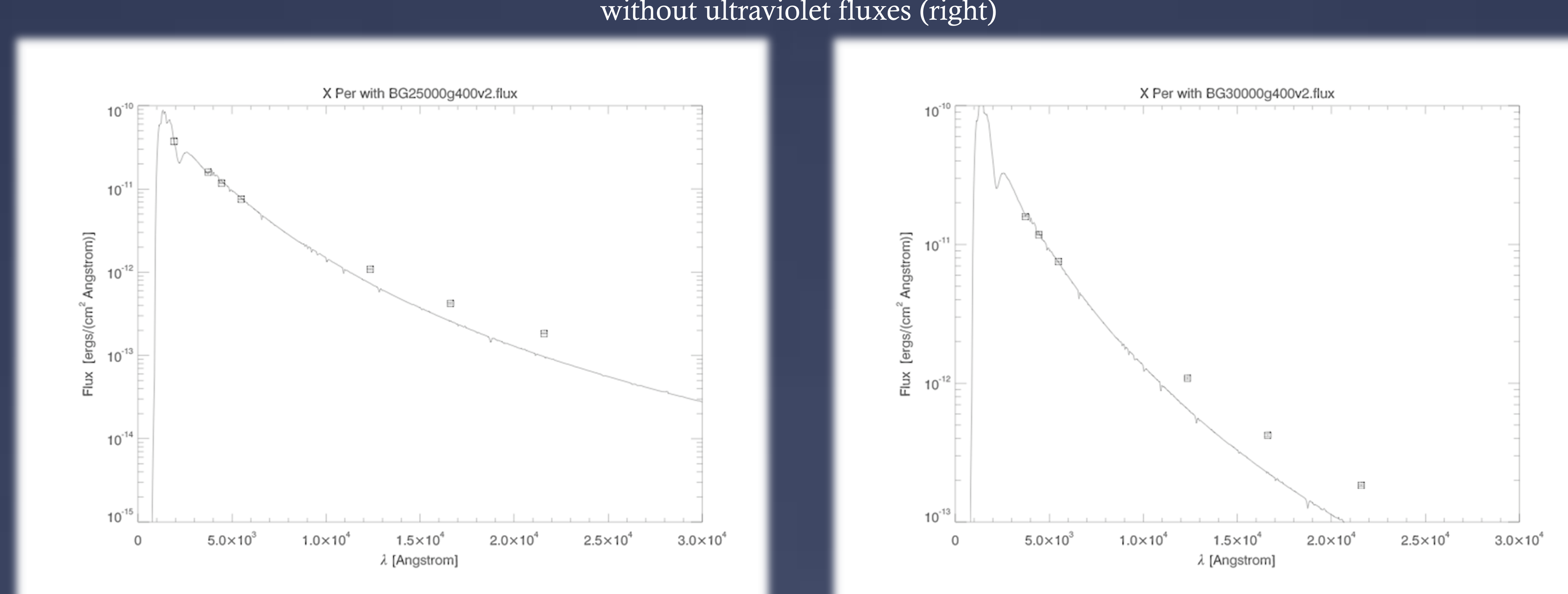

Figure 3: Observed flux points of X Per with the best fit stellar models with ultraviolet fluxes (left) and without ultraviolet fluxes (right)

Table 1: Sample physical properties of the Be stars from my IDL program

Name	With ultraviolet magnitudes					Without ultraviolet magnitudes				
	R [R⊙]	d [pc]	Reddening	Temperature [K]	M [M⊙]	R [R⊙]	d [pc]	Reddening	Temperature [K]	M [M⊙]
γ Cas	4.67	52.20	0.0	16000	7.96	7.58	184.59	0.0	30000	20.93
X Per	6.23	589.20	0.3	25000	14.13	7.58	875.08	0.3	30000	20.93
V884 Sco	7.58	584.72	0.5	30000	20.93	7.58	701.07	0.4	30000	20.93
μ Cru	N/A	N/A	N/A	N/A	N/A	4.82	204.78	0.1	17000	8.47
BZ Cru	N/A	N/A	N/A	N/A	N/A	7.58	392.26	0.4	30000	20.93
V420 Aur	N/A	N/A	N/A	N/A	N/A	7.58	1444.40	0.2	30000	20.93

References

Ankay A., et al. 2001, A&A, 370, 170-175

Cutri R.M., et al. 2003, 2MASS All Sky Catalog of point sources (CDS/ADC Collection of Electronic Catalogues, 2246, 0)

Fitzpatrick, 1999, PASP, 111, 63

Henize K.G., Wray J.D., Parsons S.B., & Benedict G.F. 1979, Catalog of Far-Ultraviolet Objective-Prism Spectrophotometry: Skylab Experiment S-019 (NASA Reference Publ. 103)

Hoffleit D., & Warren Jr W.H. 1991, The Bright Star Catalogue (5th Revised Ed.)

Jaschek M., & Egret D. 1982, Catalogue of Be stars (IAU Symp. 98, 26)

Kharchenko N.V. 2009, All-sky Compiled Catalogue of 2.5 million stars (Kinematics and Physics of Celestial Bodies 17, 409)

Lanz, T., & Hubeny, I. 2007, ApJS, 169, 83

Liu Q.Z., van Paradijs J., & Van den Heuvel E.P.J. 2001, Catalogue of X-ray binaries, A&A, 368, 1021

Liu Q.Z., van Paradijs J., & Van den Heuvel E.P.J. 2006, Catalogue of high-mass X-ray binaries in the Galaxy (4th edition), A&A, 455, 1165-1168

Oja T. 1991, A&AS, 89, 415-419

Perryman M.A.C., et al. 1997, A&A, 323, L49-52

Roeeser S., Demleitner M., & Schilbach E. 2010, AJ, 139, 2440

Van Leeuwen F. 2007, A&A, 474, 653-664

Zacharias N., et al. 2005, Naval Observatory Merged Astrometric Dataset (San Diego AAS Meeting, January 2005)

Results and Discussion

Using my program with UBV wavelength bands and ultraviolet fluxes, the distances of the bright Be stars, especially γ Cas, agree with the values obtained by trigonometric parallax with error of 30%. However, the distances improved to within 5% when using only UBV wavelength bands. Moreover, using only UBV yields better results for radii, effective temperatures, magnitudes of interstellar reddening, masses, and spectral types of the Be stars in comparison to the accepted results from the other methods. However, including ultraviolet fluxes yielded a result far from accepted models and also showed no near infrared excess fluxes as expected for the circumstellar disk, as seen in Figure 2 and 3. The problem might due to the fact that very bright targets such as γ Cas have nonlinear effects on the ultraviolet detector used to create the data sets, causing the ultraviolet magnitudes to be unreliable. Also, I could improve the distances and radii calculation by including better measurements of effective temperatures and the temperature-radius relationship for Main Sequence stars.

In the future, I will modify the fitting procedure to be able to include estimated errors of radii and distances by finding the models that yield acceptable reduced χ^2 values instead.

The relationship between H-alpha equivalent widths and the color indices in the near infrared region should be linear since both quantities are influenced by the size of the Be star's disk. My attempt to fit the color indices E(J-H), E(H-K), and E(J-K) versus the H-alpha equivalent widths of 14 Be stars yielded huge scatters and large χ^2 values rather than a significant correlation. The color index E(H-K) and H-alpha equivalent width showed the most promising correlation as seen in Figure 4, even though the reduced χ^2 value of this data set (= 5.45) is above 1.00. Therefore, I decided not to use this color index and H-alpha equivalent width relationship to determine the radii of the Be stars' circumstellar disks. The scatter might be due to the nature of the Be stars themselves. Be stars often have transient behavior since their disks can appear and disappear over time. To solve the problem, we need data collected in the same month.

My program also yielded the excess fluxes in near infrared JHK wavelength bands, which are due to the thermal radiation of the circumstellar disks. These data will benefit future work in finding the size of the circumstellar disk using a fitting approach that compares the excess fluxes to the spectral energy distribution curves of thermal radiation.

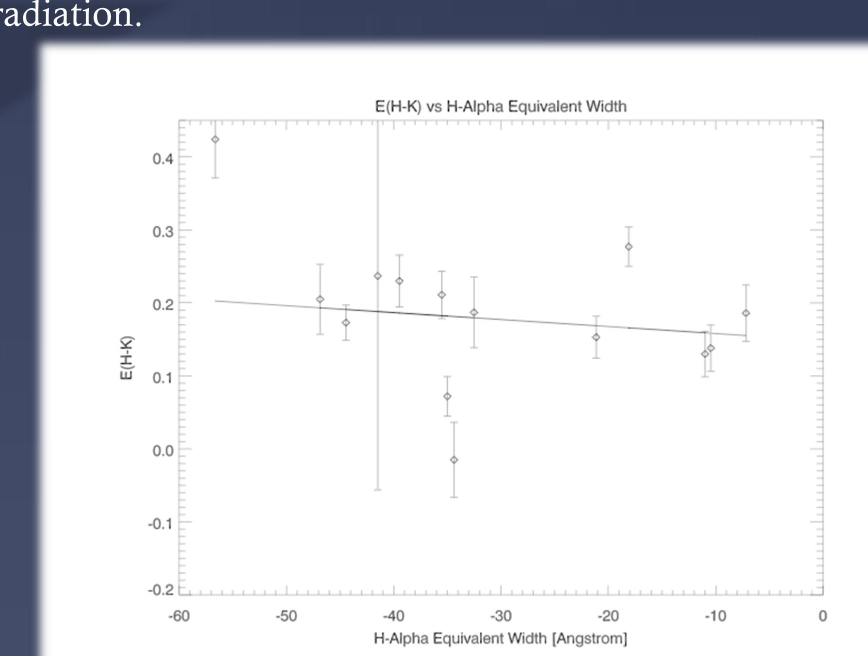

Figure 4: Linear fit of the color index E(H-K) versus H-alpha equivalent width of 14 Be stars

Error Analysis

The errors of the ultraviolet fluxes and JHK were provided by Henize et al. (1979) and Cutri et al. (2003), respectively. However, the Johnson UBV errors were not provided in some cases. Thus, I averaged the magnitudes from various sources to find the errors as follows:

$$M_{error} = \frac{1}{N-1}\sum_{i=1}^{N}|M_i - M_{avg}|$$

The errors of the color indices (e.g. CI = H – K) are expressed as the following equation:

$$CI_{error} = |dCI| = \sqrt{\left(\frac{\partial CI}{\partial H}dH\right)^2 + \left(\frac{\partial CI}{\partial K}dK\right)^2} = \sqrt{dH^2 + dK^2}$$

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