Mass Transfer in Binary Stars

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Abstract

In this paper, I investigated the properties of mass transfer in binary stars. In order to do this, I utilized the Roche Lobe model to categorize the systems in detached, semi-detached, and contact. I then investigated the process of mass transfer within those types of systems. I used the systems Vela X-1, V404 Cygni, and W Ursae Majoris as examples of each type of system, using data from each. Furthermore, I corroborated this data from a dataset generated from POSYDON of a million binary stars. I found the local populations on an HR diagram of each system and found the main causes of mass transfer in detached systems to be wind accretion, semi-detached to be Roche Lobe overflow, and contacts to be direct mass sharing. Additionally, I found properties in both W UMa and V404 Cygni which warrant further investigation.

Introduction

Most of the stars we see in the night sky are not actually single stars, instead consisting of multiple stars orbiting a common center of mass. A pair of such stars is called a binary. These binaries are formed in the same nature of single stars, that being through a molecular cloud. However, due to instability in the formation process, two or more stars are formed instead of one [1]. These stars orbit a common center of mass. The stars in these binary pairs will a have a different evolutionary track on a HR diagram then a single star, as it is highly likely for the two stars to interact at some point during their life because of their proximity in formation [2]. As these stars evolve and interact with each other, it drastically affects their evolution.(see fig. 1)

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1.1 Mass Transfer in Common Binaries

In systems with small orbital separations and a large mass ratio a process called mass transfer can occur [3]. This is where one star called a donor will “donate” mass to the other star, called the accretor. This is likely to occur at some point during the binaries’ lifespan, leading to different evolutionary outcomes as compared to single star evolution [3] (see fig. 1). However, depending on the duration of mass transfer and the star type, this process can be hard to detect observationally. Because of this, a large of studies is conducted on binaries with more extreme star types, such as neutron stars or black holes, where the process of mass transfer leads to much more pronounced effects. This is because as the mass is transferred to the BH or NS the process leads to a large spike in X-ray emissions (sect. 1.6.1), which can more easily measured as compared to the mass transfer process between, for example, a red giant a main sequence star, which have little to no x-ray emission.

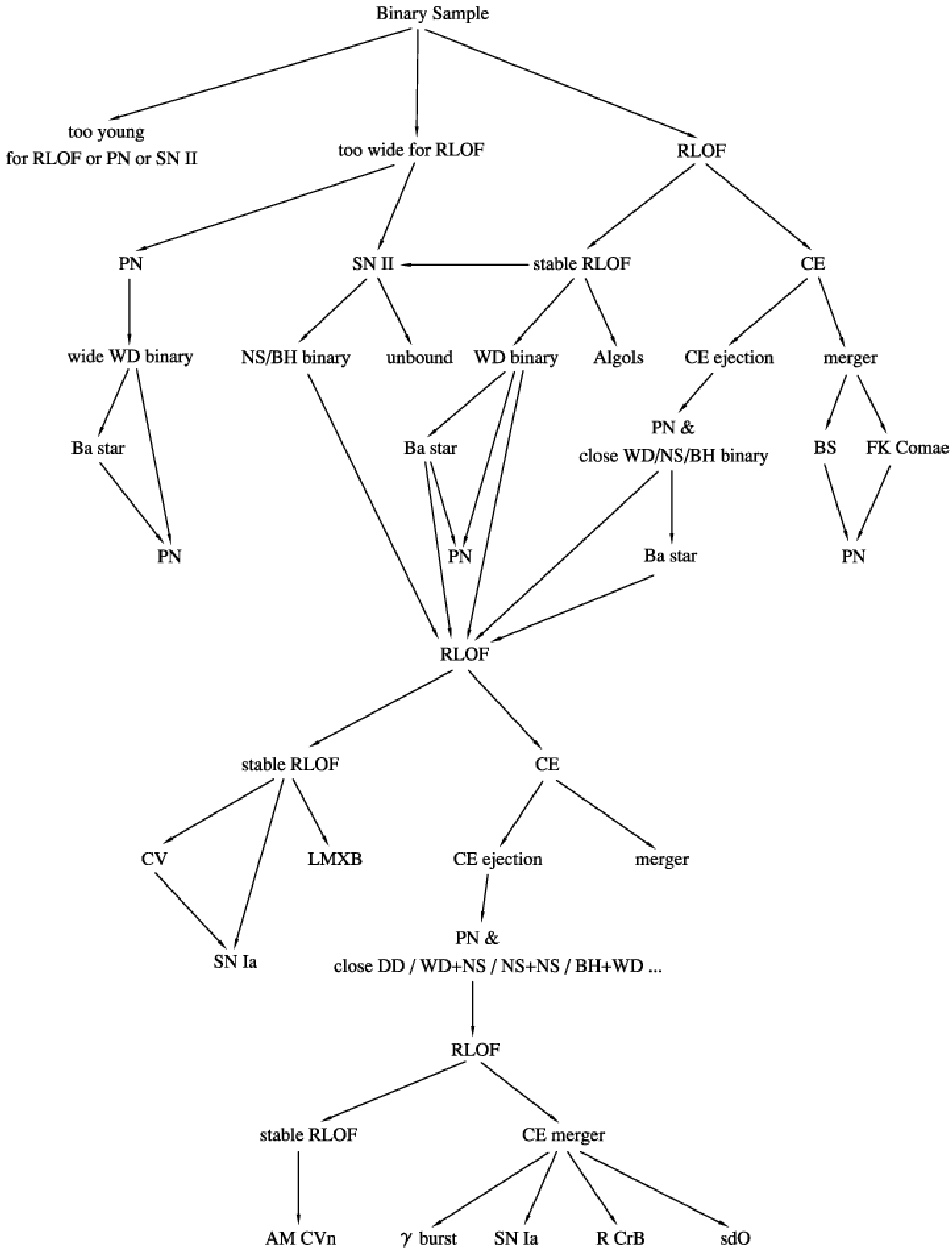


Figure 1: *A heavily simplified flowchart of binary evolution. Reprint from [4]. See much more in depth version in [5]*

1.2 Roche Lobe Model

The Roche Lobe (RL) model was proposed by Édouard Roche and defines the gravitational potential of a binary through a simple model. Simply put, it defines the region around a star where it can hold onto it mass (i.e. great enough gravitational potential). If one of the stars in the binaries' mass overflows said lobe, it will transfer mass to its binary pair. This model can be used to classify binary star populations into various populations, including **Detached Binaries** (where neither star has filled their potential), **Contact Binaries** (where both stars have filled their potentials), and **Roche Lobe Overflow**(RLO) systems (where one star has filled its potential, leading to mass transfer to an accretor).

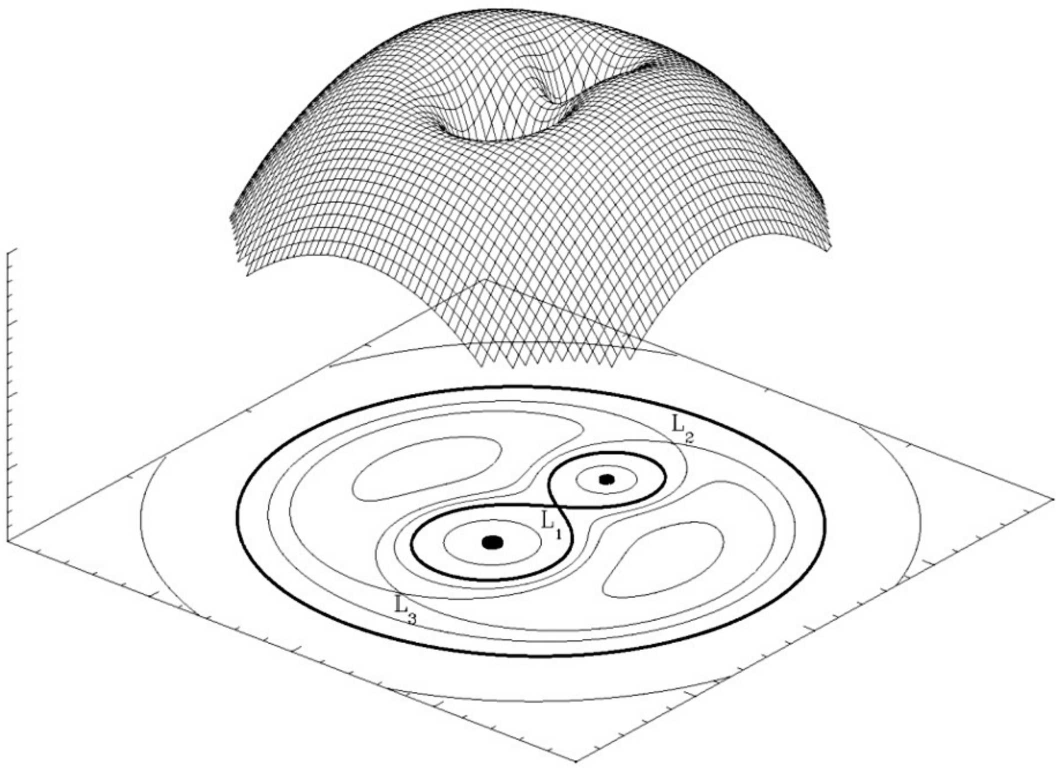
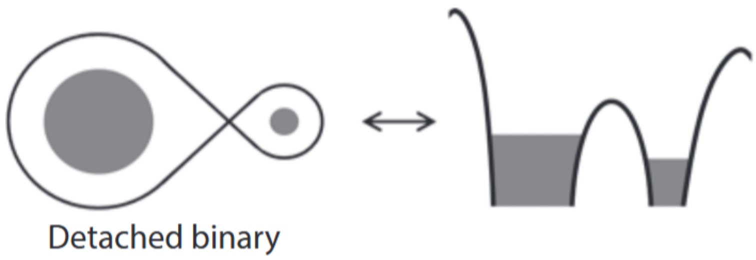


Figure 2: *A 3D representation of the gradient of the Roche lobe*
Reprint from [6]

1.3 Detached binaries



Reprint from [3]

Figure 3: *Graphic of the RL model with regard to how much potential is being filled in a detached binary. Note here that has both a 'top-down' perspective and from the side.*

Systems where neither star fills its potential fully (see fig. 3) are called detached binaries. Despite the fact that these systems have not filled their Roche Lobes, mass transfer is still possible through a processes called wind accretion (see 1.3.1). We see this predominantly in systems called *High Mass X-ray Binaries*, where a supergiant star transfers mass to a compact object via wind accretion. This process leads to an increase in X-ray Emission (sect. 1.6.1), which we can easily measure [3]. It is important to note the majority these systems are not experiencing full-blown RLO (sect1.4), however, they tend to be incredibly close to doing so [3]. It is important to note that these systems transfer can transfer mass through wind accretion, atmospheric Roche Lobe Overflow, and full-blown RLO.

I used the system Vela X-1 [7] as an example of this, as it is generally regarded as the "archetypical wind accretor" [7]

1.3.1 Wind Accretion Mass Transfer

Wind accretion is very different from normal mass transfer in a binary. All stars produce 'wind,' i.e. mass which is pushed away from the star. Most stars cause a process called stellar wind, occurring when mass from the outer envelope is ejected at speed from the star. All stars have experience varying strengths of stellar wind, with some winds having very high velocities, and others much lower. [8] In binary stars this process allows mass to be transferred from a donor to accretor.

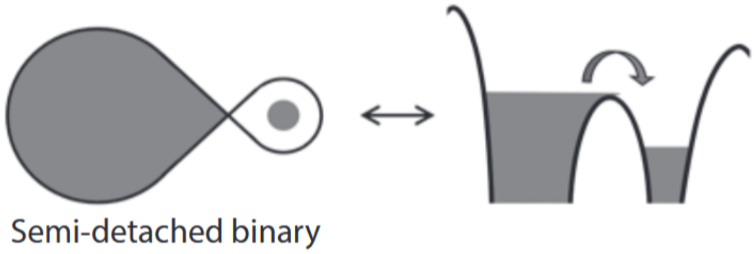


Figure 4: *Reprint from [3]*

1.4 Semi-detached Binaries

In systems where one star fully fills its RL (sect. 1.2, fig. 4) mass begins to be transferred to its binary partner. This is process is called Roche Lobe Overflow (RLO) and is defined by a donor and accretor star (sect. 1.1). This is incredibly likely to happen at some point in a binaries' lifespan drastically affecting the course of evolution [3][5]. Depending on the systems star types, masses, and orbital eccentricity, this process of mass transfer will either be stable or unstable. When this process if unstable, it leads to either another stage called common envelope (sect. 1.5.1) or a rapid merger [3]. However, if the process of mass transfer is stable, the two stars will remain detached, slowly exchanging mass [5] [3].

We are able to observe this very commonly in Low Mass X-ray Binaries, where a donor star transferred mass to an accretor which is a compact object (a black hole or neutron star). This process produces X-rays (sect. 1.6.1) which we can measure to understand the processes within the binary in greater detail.

This process, similar to section 1.5.1, can be either stable or unstable. A large factor which determines this stability is the evolutionary stage of the donor star [3], as upon the onset RLO, some donors stars' radius will increase, leading to even more rapid RLO. This is primarily due to the nature of the stars' envelope, with radiative envelopes shrinking upon mass loss and convective envelope swelling [3].

In intermediate mass x-ray binaries, a system will survive this process of mass transfer if the unevolved or early stage donor star mass is between $2 < M_2/M_\odot < 5$ [3]. In low mass x-ray binaries (LMXBs) it is $M_2 \gtrsim 1.8M_\odot$. Systems with $M_2 > 2$ Will be unstable for giant donors in later stage RLO [3].

I used the system V404 Cygni (15) with data from [9] and [10] as an example of this behavior, as its magnitude, proximity to Earth, and quantity of studies make it an ideal choice to understand how systems like it behave.

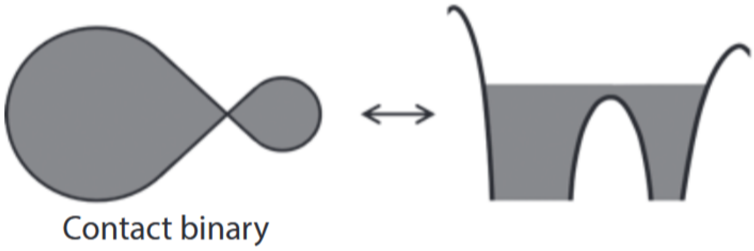


Figure 5: *Reprint from [3]*

1.4.1 Mass transfer through L_1

In this process of mass transfer, the mass will be transferred through the Lagrangian point L_1, as it is the point of lowest potential between them, as seen in figure 2 [3]. The mass at L_1 feels an equal gravitational pull from both stars. The mass is then transferred through a pressure differential, where the donor star pushes the mass through.

1.4.2 Atmospheric RLO

1.5 Contact Binary

In binaries with prominent RLO it is possible for the donor star to fill up not just its own Roche Lobe, but the accretors' as well. This means that both the donors potential and the gravitational accretors potential are filled. [3] As these stars have both fully filled their RL's, they transfer mass by physically being connected. This process of mass transfer can theoretically lead to mass transfer oscillating between which of the two stars is the donor (sect. 1.5.3).

If both of the binaries' potentials are full, then donor star will then begin to fill up the systems total gravitational potential (i.e. the area between the two ridges in fig. 5). This can lead to mass being loss from the system completely [3], forming a formation similar to a planetary nebula.

This process generally is not stable, as most stars this in stage generally are experiencing a brief stage of their evolution called common envelope (CE). (See section 1.5.1) However, in cases where it is stable, the stars will continue to evolve as one body (sect. 1.5.2).

1.5.1 Common Envelope (CE)

CE occurs in a binary system after runaway mass transfer which leads to the companion star being fully engulfed in the envelope of the donor [3]. This leads to forces which greatly reduce the orbital separation. This can either cause the two stars to merge within the environment or for the envelope to be ejected. The ejection of the envelope can allow for the two systems to remain detached, however, the stars are likely to merge in the process [3] (sect. 1.3). This ejected mass can either orbit around the system, or be fully ejected from the system, which is a likely cause of planetary nebulae [3]. There are many questions about this process, as the short yet incredibly rapid evolution is incredibly difficult to model. [3]

1.5.2 Stable Evolution

In systems which are stable the stars will share mass and that their shells will evolve in tandem, this process is called "homogenous chemical evolution". (See fig 1 [5]). As these stars transfer mass, their mass ratio (q) will oscillate around a value of $q = 1$, eventually reaching q_{min} at which point the stars will rapidly merge (see fig. 6) [11]. These systems are rare as they require the two stars to have a similar mass [3].

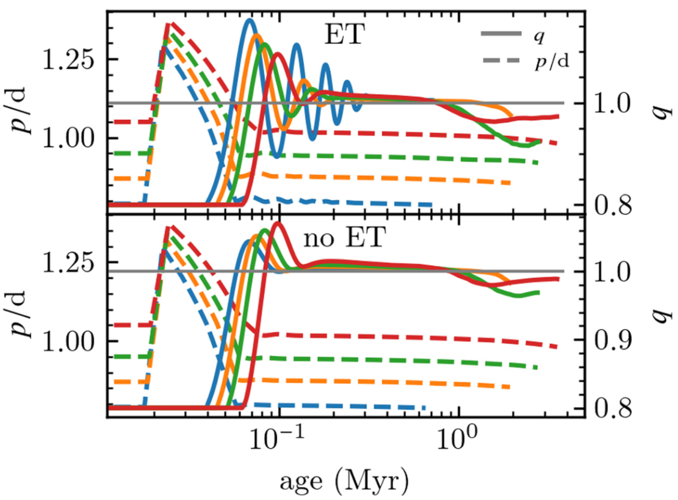


Figure 6: *Reprinted from [2]. These graphs show the effects of modeling energy transfer(ET) on the systems' evolution.*

1.5.3 Mass Transfer Oscillation

1

I used W Ursae Majoris (W UMa) (sect. 3) as an example of these systems, as it is used an example system in order to categorize these contact binaries as a whole.

[1]This is a largely theoretical model proposed by [2]

1.6 X-ray Binaries

1.6.1 X-rays caused by accretion onto a compact object

In 1962 the first X-ray binary was discovered by Riccardo Giacconi and colleagues. This system, Scorpius X-1, is so bright in x-ray that it actively raises ionization levels in Earths atmosphere when above the horizon. [3] [12] In the years following, it was discovered that that Scorpius X-1 consisted of a normal star and neutron star. Since then, many thousands more have been discovered[13].

These x-rays are produced from the friction of in-spiralling matter, which causes it to become incredibly hot, with the inner disk reaching temperatures of ≥ 10 million K, causing it to emit a large amount of x-rays. In systems with a NS accretor, the surface of the NS itself will also emit a large amount of x-rays [3] (fig. 7).

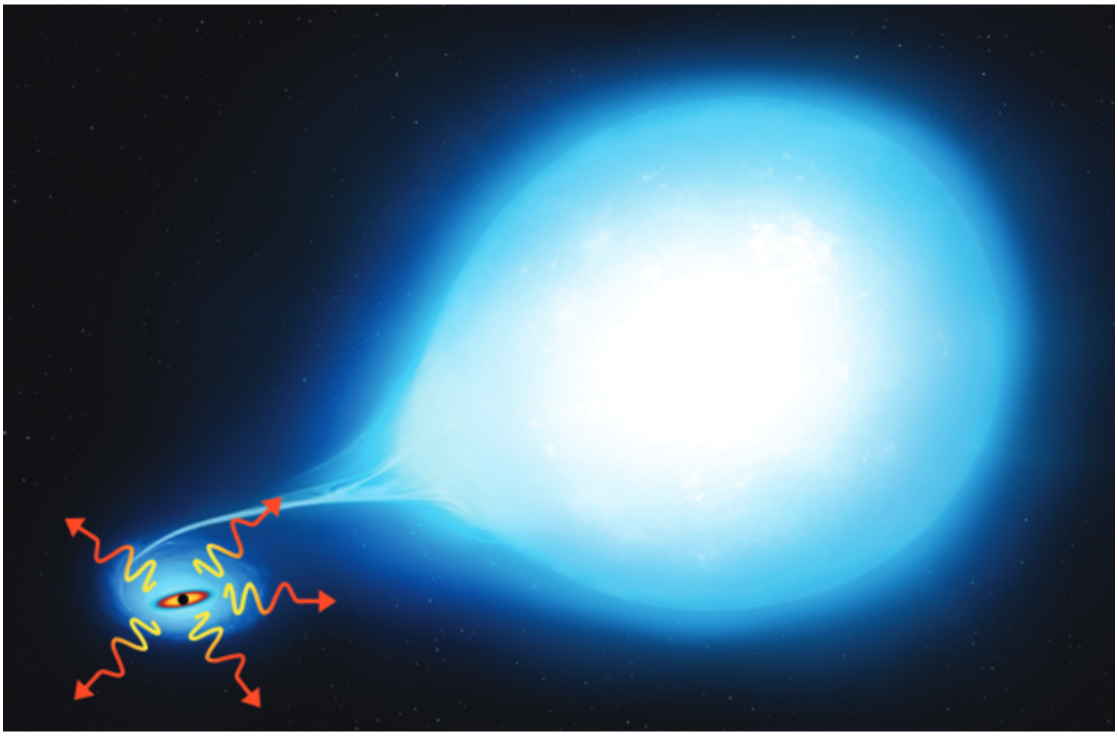


Figure 7: *Reprinted from [3], original work by Mark Garlick, ©Mark Garlick. Here we see matter from a normal star falling onto a compact object, with the compact object being the source of x-rays*

Data Acquisition

2.1 Vela X-1 (Detached)

2.1.1 Known properties

	Vela X-1 A	Vela X-1 B
Star Type	Neutron Star	Supergiant [7]
Masses$M_{\odot}$	≥ 1.8 [7]	20–30 [7]
Radius	11-12.5$_{KM}$ [7]	30 $R_{\odot}$ [7]
Temperature		$33.7 \pm 5.2kK$ [7]
Luminosity		5.8-6.2$L_{M_{\odot}}$ [7]
Separation	$2kpc$ [7]	
Mass Loss Rate	$10^{-6}M_{\odot}yr^{-1}$ [7]	
Eccentricity	$e \approx 0.0898$ [7]	

Table 1: *Properties of Vela X-1*

Vela X-1 consists of a Neutron Star and Supergiant and is an Eclipsing and pulsing high mass x-ray binary (HMXB). This means that the Neutron star passed behind the Supergiant every 8.94 days [14], leading to a variable luminosity between 10^{36} $erg\ s^{-1}$ and 10^{37} $erg\ s^{-1}$. Additionally, the neutron star itself is spinning every 293 seconds. [7].

Vela X-1 is described as an archetypical wind accretor, as it is a system which is undergoing wind accretion in a stable, predictable, and easy to measure way. The x-ray emission is persistent as well having prominent broadband spectra. Having both x-ray and broadband allows both to be measured and compared. Astronomers use Vela X-1 as examples when looking at other systems with comparable x-ray emissions [7].

The wind accretion (see 1.3.1) comes in the form of wind from a supergiant star (Vela X-1B) falling onto the neutron star. This wind does not have a very high velocity, but because the supergiant has almost filled it RL [7], the wind mass can easily escape, falling onto the NS. This accretion process (Sect. 1.6.1) is what creates the prominent X-ray emission.

2.2 V404 Cygni (Roche Lobe Overflow)

2.2.1 Known properties

	V404 Cygni B (Donor)	**V404 Cygni A (Black Hole)**
Star Type	Early K-type Giant	Black Hole
Masses	$.7_{M_\odot}$ [9]	$9_{M_\odot}$ [10] [15]
Radius	$6.0_{R_\odot}$ [10]	
Temperature	4274^{+116}_{-113K} [15]	
Luminosity	$8.7^{+1.7}_{-1.4L_\odot}$ [15]	
Distance	2390_{pc} [9]	
Orbital Period	$6.73 \pm .001$ [15]	

Table 2: *Properties of V404 Cygni*

V404 is a LMXB, meaning that the donor star has a relatively low mass. In this system the material being accreted by V404 Cygni A forms an accretion disk, which greatly increases the luminosity of the system (**sect. 1.6.1**). This mass is transferred directly through L_1 (**sect. 1.4.1**) [16]. V404 is also a variable star system, with is magnitude varying overtime [9]. The reason why is currently under great discussion, there are two current likely causes. That being that either the donor star begins to release mass at a greater rate [17], or due to instability in the accretion disk itself [18]. This is a property which is commonly observed in LMXBs.

2.3 W Ursae Majoris (Contact Binary)

2.3.1 Known properties

	W UMa A	W UMa B
Masses$M_\odot$	1.139 ± 0.019[19]	0.551 ± 0.006[19]
Radius$R_\odot$	1.092 ± 0.016[19]	0.792 ± 0.015[19]
Temperature$K$	6450 ± 100 [19]	6170 ± 21 [19]
Luminosity$L_\odot$	1.557 ± 0.166[19]	0.978 ± 0.071[19]
Distance	$52pc$ [20]	
Max Magnitude	7.75 [21]	
Min Magnitude	8.48 [21]	
Period	.3336 *days* [19]	
Inclination Plane	$88.4 \pm 0.8°$ [19]	

Table 3: *Properties of W Ursae Majoris*

W UMa is a contact binary, meaning that the two stars are physically 'connected' by their mass. This system is known as an archetype because is it has a high magnitude at 7.75 at peak and 8.48 at minimum (table 3), meaning that its fairly easy to observe the variability. We can measure said variability in the form of light curves, which reveal a distinct nature different which is different from non-contact binaries (fig. 8). This magnitude variability is due to the fact that the binary is eclipsing due to its low inclination plane (table 3), meaning that the stars will pass behind each other in their orbit relative to the Earth.

Because of the prominent nature of this binary, similar contact binaries are called referred to as 'UWMa type' if they also possess said eclipsing nature.

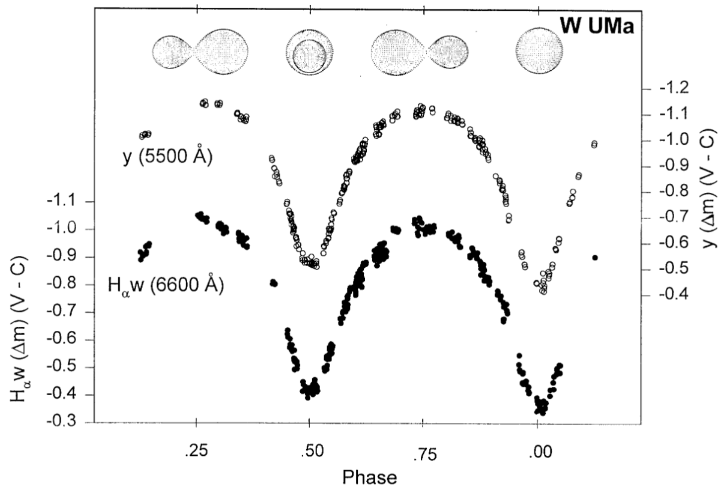


Figure 8: *Reprint from [22]*

2.4 POSYDON Simulations

I used data generated by POSYDON [23] in corroboration with three observed systems in order to fully understand the depth of the process of mass transfer in Binary Systems. This is because while catalogues of contact binaries, HMXBS and LMXBs exist, there is not enough of them to get a true grasp of the full picture. Hence, I used POSYDON. This dataset was simulated on the NU Super computing Cluster, QUEST. POSYDON is developed and maintained by a team of astrophysicists and computer scientists working at the Université de Genève and Northwestern University. POSYDON uses an additional script called MESA, which is dedicated to single star and binary evolution. POSYDON utilities MESA on a much larger scale in order to simulate full populations. The data was stored in the form of a .h5 file, containing a total of 6,128,390 rows and 83 columns. (See greatly reduced example of the data frame in (table 4) and an HR Diagram of the full dataset in fig. 9)

Binary ID	System State	Orbital Period (days)	$\log_{10}$ Mass Transfer Rate	Donor State	Donor Mass $M_\odot$	Accretor State	Accretor Mass $M_\odot$
54	Detached	0.047520	-99.00000	NS	1.196033	stripped He Core He burning	≈ 1.002
183	Detached	0.0429883	≈ -80.8	NS	1.196033	stripped He Core He burning	$\approx .9957$

Table 4: *Example of POSYDON data, heavily modified for readability*

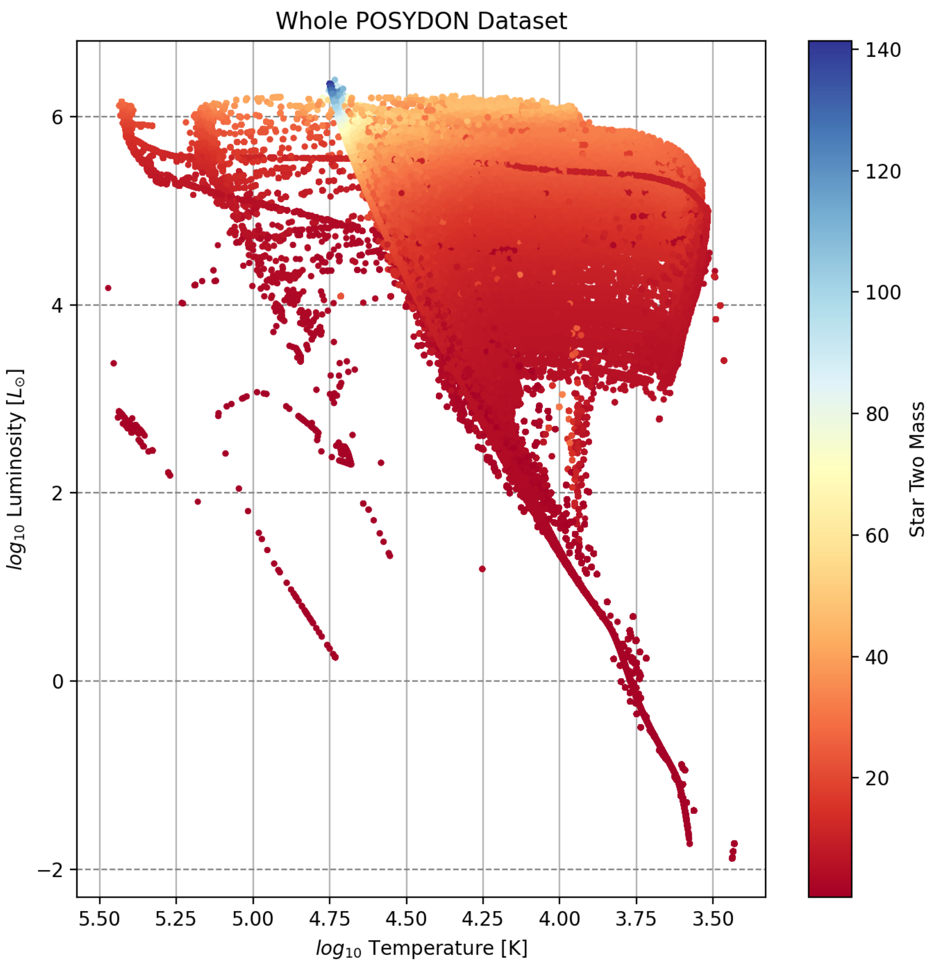


Figure 9: *HR Diagram of the donor star for the full ($\tilde{6}.4$ million points) POSYDON dataset. Note that the color of the plotted points correspond to the solar mass of the donor star. Generated with Matplotlib*

This dataset looks very similar to a standard HR diagram, however, there are some key population differences. In the center we can see the Main sequence

2.4.1 Data Processing

With my research I sought to contextualize these very specific systems, allowing one to better understand how these systems play into the larger picture of binaries. In order to do this I utilized a large dataset generated from POSYDON. In order to properly analyze this data I utilized Python with a large quantity of packages. These packages included Pandas [24], Matplotlib [25], and NumPy [26]. These tools allowed me to rapidly and efficiently analyze the large amount of data, something this paper would not have been possible without.

Results

Through my research I found a number of interesting discoveries, both regarding the populations of binaries as a whole, but also some applicable to systems themselves.

3.1 Detached Binaries

I found that despite the fact that detached systems are, as the name suggests, detached, they very much so can still transfer mass. In fact, they have a multitude of ways which they can transfer mass [3]. When looking at detached systems which experienced mass transfer a large quality of them were referred to as HMXBs. This is due to a process called wind accretion (sect. 1.3.1), where a star of great enough mass is able to transfer some of that mass through stellar winds [3]. However, these systems, while being technically detached, are incredibly close to filling their RL (sect. 1.2). Because of this, it is not unheard of for them to also transfer mass through full-blown RLO (sect. 1.4) ([3]). Additionally, their atmosphere can be transferred through RLO while their mass itself is not, in which case it is called atmospheric RLO (sect. 1.4.2).

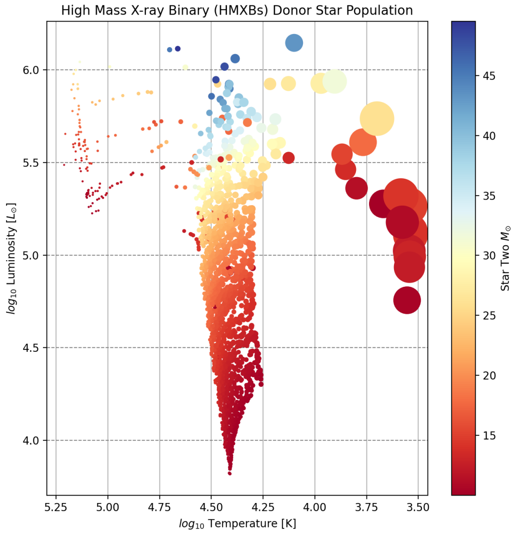


Figure 10: *HR Diagram of HMXBs using POSYDON generated data. The size of the plotted dot corresponds to the size of the star.*

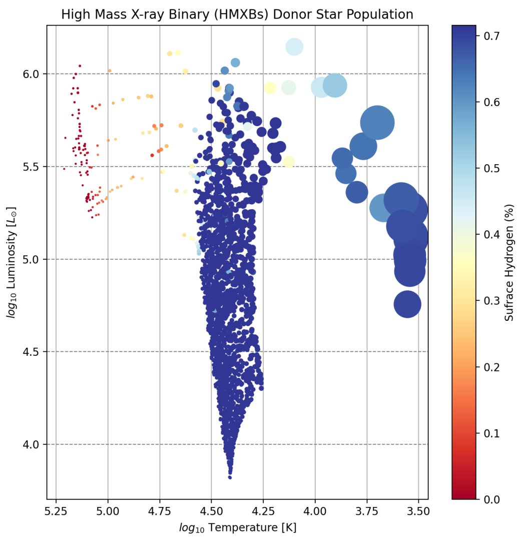


Figure 11: *HR Diagram of HMXBs using POSYDON generated data. The color the star corresponds to the percentage amount of surface hydrogen.*

In figure 10 we can see that while the majority of the donor stars in HMXBs are main sequence, a large quantity of them are also Wolf-Rayet type (see fig. 11) and supergiants (see size of the stars in fig. 10).

3.1.1 Vela X-1 Results

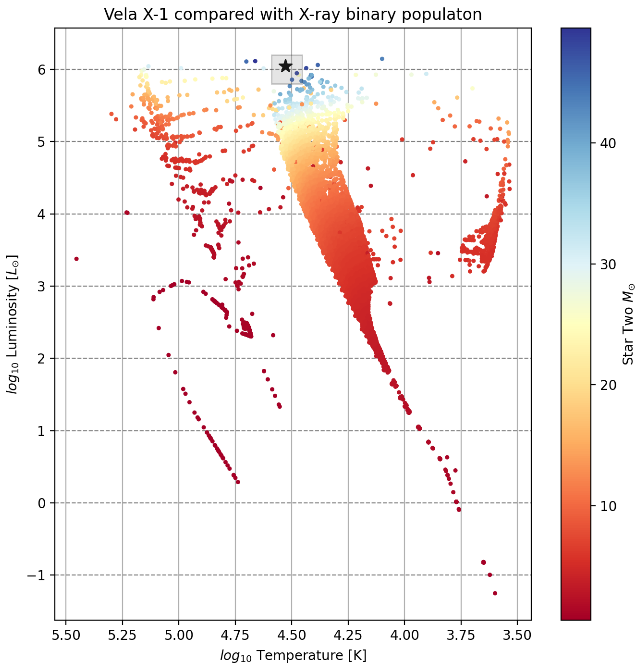


Figure 12: *HR Diagram with reference for Vela X-1. The star is the mean value of observation range, box is overlap of the max and min temperature and luminosity values.*

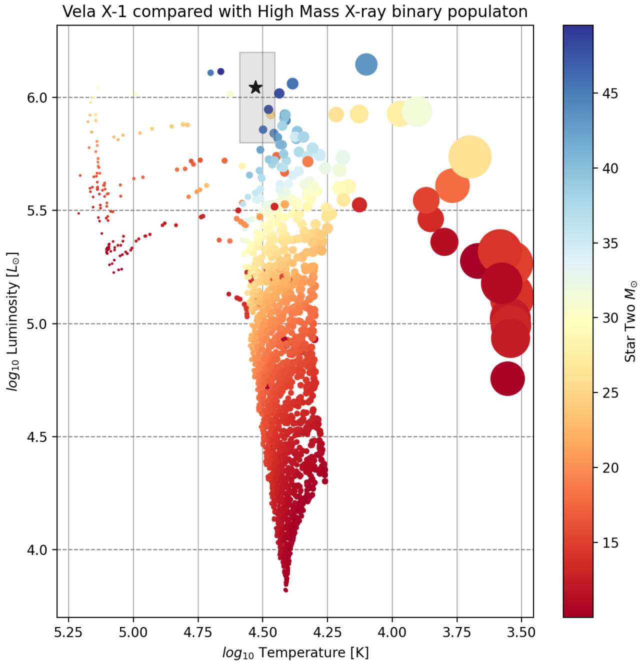


Figure 13: *HR Diagram of HMXBs with reference point for Vela X-1. The star is the mean value of observation range, box is overlap of the max and min temperature and luminosity values.*

In figures 12 and 13 we see that Vela X-1 is one of the more extreme example of HMXBs, as it has a higher temperature and luminosity then a lot of its similar stars, the majority of which are in main sequence. We can also confirm the fact that Vela X-1 is a giant star due to its location and proximity to other giants on the HR Diagram (fig. 13), something which is corroborated by [7]. However, in terms of giant stars in binaries, it is not the most extreme, falling within the norm.

3.2 Semi-Detached Binaries (RLO)

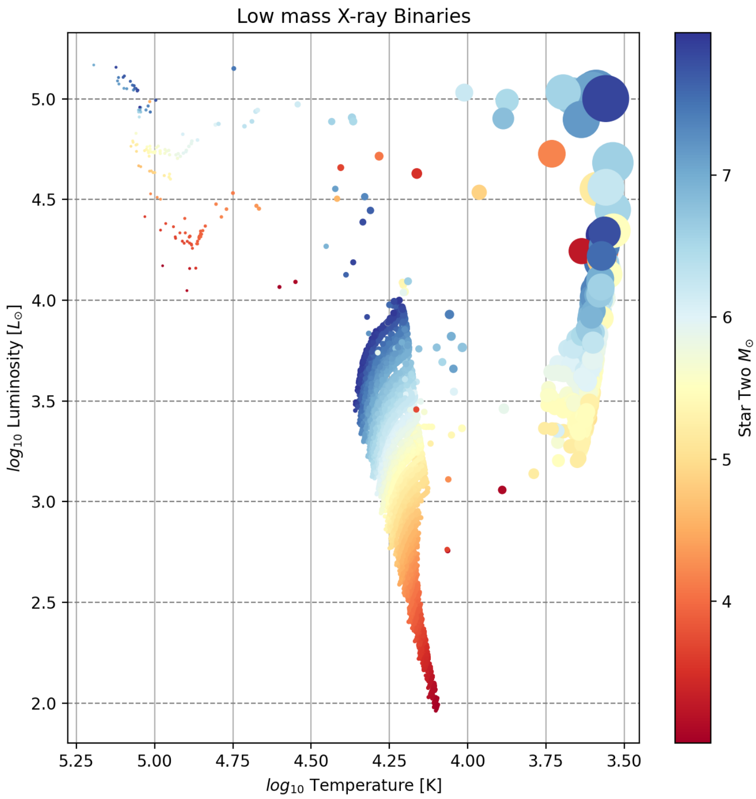


Figure 14: *HR diagram of the donor star in Low mass X-ray Binaries. Size of the plotted dot corresponds to the size of the star.*

I learned that RLO a very common phenomena in binary star evolution, with the majority of systems undergoing it as an evolutionary phase during their lifetime [3]. I found that it is most commonly and directly observed in LMXBs [3], as these systems can allow for a stable transfer of mass from a donor to an accretor, which can create emission of x-rays ([3]) (sect. 1.6.1). Furthermore, I found that RLO can either be stable or unstable and that some of the most important factors in stability are the mass ratio of the stars, the eccentricity of the system, and the stars' envelope type (sect. 1.4). I found that this mass is transferred through the Lagrange point L_1 due to a pressure differential [3] (sect. 1.4.1)

In figure 14 we can see that X-ray binaries' donor stars generally follow a semi-standard HR diagram.

3.2.1 V404 Cygni Results

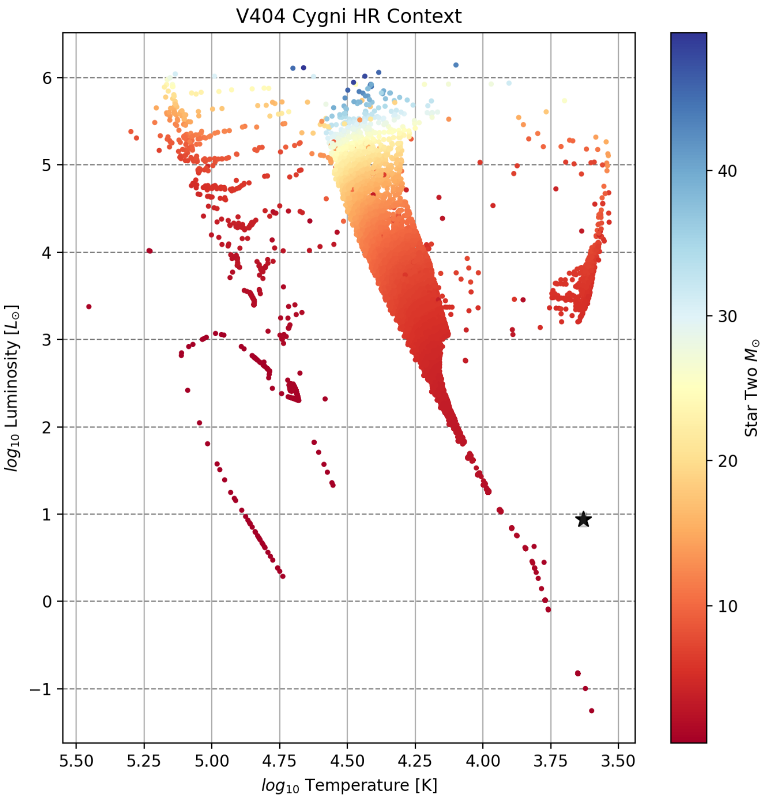


Figure 15: *HR Diagram with reference for V404 Cygni. Utilizing data from [16]. Note that the range of error is plotted, however, does not play an effect on the location of the star*

I discovered that V404 Cygni does not fall onto the two main simulated evolutionary tracks for LMXBs. This distinct discontinuity between the observed temperature and luminosity and what makes sense for a location on an HR diagram suggests that one of the two is off. It is, of course, more likely that the simulated data possess the error, as V404 has been measured a multitude of times. I believe this discrepancy comes from V404 Cygnis' unique properties (table 2). It is uncommon for a star to lose such a large amount of mass and be so tightly constrained to its accretor as we see in [16]. I believe this is the cause of the discrepancy, as the simulated software most likely not account for such extreme cases. However, further investigation of both the simulated and the observed data is needed to get a full conclusion.

While investing this I tried a multitude of different things. This included getting more recent data of V404 Cygni from [16], graphing an error range around the plotted star (fig. 15), and plotting the entire dataset including all the stars evolution over time (fig. 16). None of these lead to any breakthroughs.

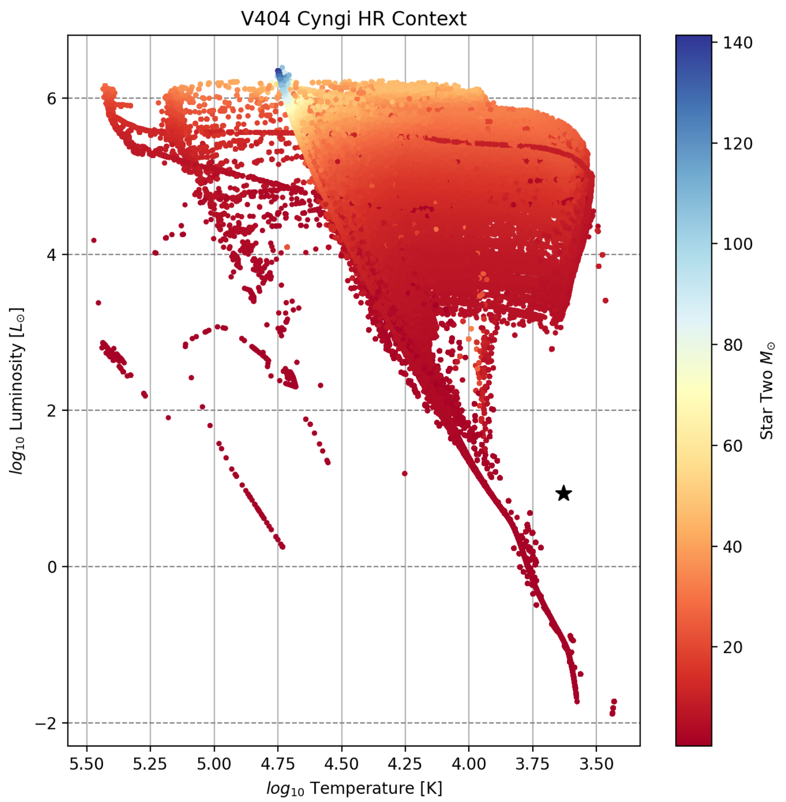


Figure 16: *HR Diagram with reference for V404 Cygni. Utilizing data from [16]. Still off of any plotted evolutionary track despite being plotted with the entire dataset.*

3.3 Contact Binaries

I discovered that mass transfer in contact binaries happens in a variety of cases. In some systems where both of the stars RL's are full (fig 5), the system can in a multitude of states. The most prominent of these being common envelope (1.5.1) and an actual contact binary. It is important to note that CE is a *stage* which a temporary stage which many different types of binaries evolve through, whereas a contact binary is a population themselves.

I found that in mass transfer in evolving contact binary theoretically causes a mass oscillation between the two stars [2] (fig. 6), where the star stars will transfer mass back and forth. This process will continue until the mass ratio between the two stars crosses a critical threshold, after which the stars will then merge [2].

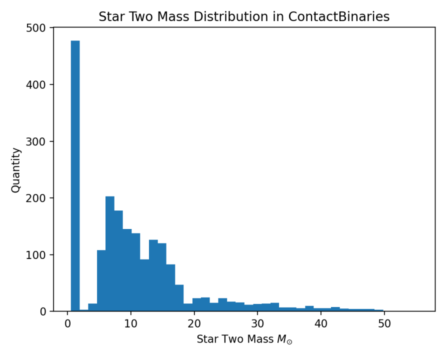


Figure 17: *Star two mass distribution for contact binaries*

In figure 17 we can see that contact binaries mass distribution feature a prominent spike at around one solar mass, with a distribution centered around 10, and then a scattered amount afterward.

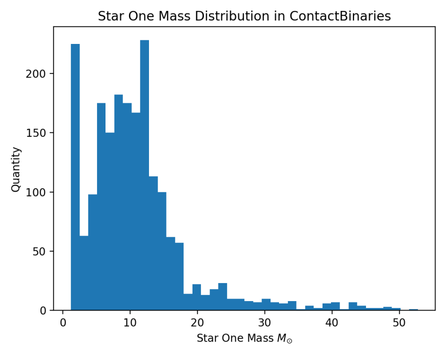


Figure 18: *Star one mass distribution of contact binaries*

Note how similar this is to the star two distribution. From the POSYDON data, I found the mean mass of star one in contact binaries to be ≈ 10.703 and star two to be ≈ 10.6548. This is congruent with what previous papers have found ([2]). This is due to the nature of mass transfer in contact binaries leading to a stabilization in mass. As a contact system evolves, the mass transfer causes q (the mass ratio between stars) to stabilize to a value of $q = 1$ [2]. We can clearly see this oscillation and then stabilization in **figure 6**. The cause of the difference in fig. 17 and 18 is because of the nature of the simulated data, as the initial grid was predisposed for star one binary to have a greater mass in order to increase the likelihood of mass transfer.

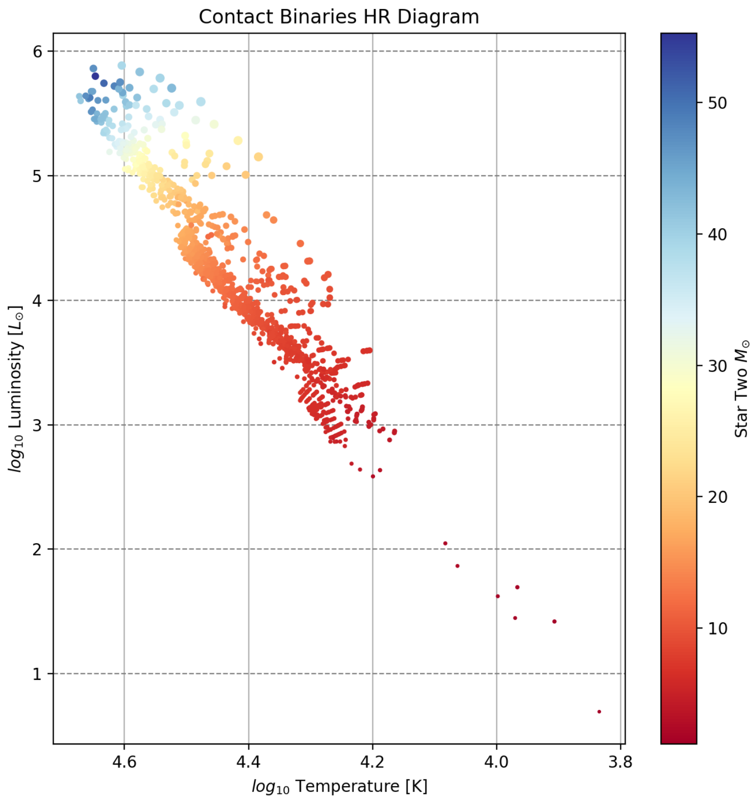


Figure 19: *HR diagram of contact binaries from POSYDON data, generated with Matplotlib.*

This is one of the more interesting results, as we can see that contact binaries form a very specific population on the HR diagram, falling on specific linear with a linear relationship (fig. 19) I believe this is because of the stabilizing natures regarding mass ratios in contact binaries. It is important to note that these values are much above what we observe in contact binaries. Again, there are many reasons this could be, including the inherent skewing of the grid, the nature of observing contact binaries, and more.

3.3.1 W UMa Cygni Results

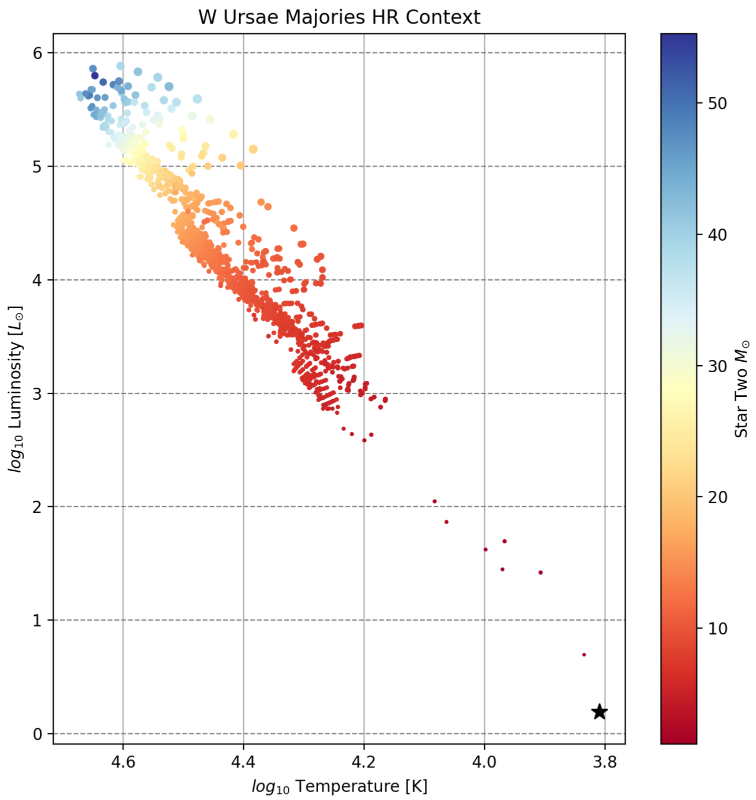


Figure 20: *HR Diagram with reference for W UMa using W UMa A. Plotted using data from*

In **figure 20** we see that W UMa also follows this linear relationship, however, it has a much lower temperature and luminosity then most of the population. This is a known discrepancy with current simulated models, where simulated values are both typically more luminous and massive than observed. [2]. There are many in line with other observed contact binaries.

Conclusion

In conclusion, I found the local populations of V404 Cygni (sect. 3.2.1), Vela X-1 (sect. 3.1.1), and W UMa (sect. 20) by graphing them on HR diagrams in regard to POSYDON data. I found the main causes of mass transfer in detached systems to be wind accretion, semi-detached to be Roche Lobe overflow, and contacts to be direct mass sharing. I found that properties both the graphs in both V404 Cyg (sect. 3.2.1) and W UMa (sect. 20) which warrant further investigation.

Discussion

Originally I planned on simulating grids for all the types of systems, however, due to time constraints I chose to only focus on one type. This proved to be the right decision, and it prevented the scope of the project from becoming too constrained.

5.0.1 Disclaimers/Notes

Due to time constraints, I was not able to cite all the sources within the textbook [3] which I used. This is because it was quite tedious to find the paper itself the textbook references.

Additionally, as this was my first project in LaTeX(sect. 5.1.2) as a freshman, I am sure there are various minor errors and things that do not fit proper convention.

5.1 Code and Writing Process

5.1.1 Code

As I analyzed the data, I found there were certain actions regarding data processing and graphing that I was doing repeatedly, so I wrote a custom Python script in order to streamline the process. This script allowed me to change minor things in the graphs (like the title of color bars) quickly and apply them to all the curated graphs. This script can be found on the GitHub page (sect. 5.1.3) for the project.

5.1.2 LaTeX

Originally, I started working on this project using Overleaf, however, due the amount of graphs, the time to compile started to rapidly climb up, and eventually I just decided to switch to compiling it locally. On-top of this, I figured I would set up a GitHub in order to additionally push the code and graphs as well. This turned out to absolutely be the right decision, giving me way more freedom.

Additionally, I wrote the entire paper in LaTeX, a typesetting system which is the standard for academic papers. I challenged myself to learn and use this format in order to prepare myself for further academia. Using LaTeX also allowed the graphs being generated by my Python scripts to automatically be imported and/or updated into the paper, saving large quantities of time.

5.1.3 GitHub

This essay, the entire paper, all of my data, code, and figures, can all be found on GitHub at `https://github.com/PiersonLip/Honors-Independent-Study`. Syncing everything to GitHub additionally allowed me to work on the paper seamlessly from multiple devices, syncing different versions with ease.

I worked on this entirely in VS Code, as it provided a great environment for me to work efficiently and its integration with Python notebooks and Git helped me work efficiently

Sources

[1] Stella S. R. Offner et al. "THE TURBULENT ORIGIN OF OUTFLOW AND SPIN MISALIGNMENT IN MULTIPLE STAR SYSTEMS". In: *The Astrophysical Journal Letters* 827.1 (Apr. 2016), p. L11. DOI: 10.3847/2041-8205/827/1/L11. URL: https://dx.doi.org/10.3847/2041-8205/827/1/L11.

[2] M. Fabry et al. "Modeling contact binaries: III. Properties of a population of close, massive binaries". In: *Astronomy & Astrophysics* 695 (Mar. 2025), A109. ISSN: 1432-0746. DOI: 10.1051/0004-6361/202452820. URL: http://dx.doi.org/10.1051/0004-6361/202452820.

[3] Thomas M. Tauris and Edward P.J. van den Heuvel. *From Stars to X-ray Binaries and Gravitational Wave Sources*. Princeton: Princeton University Press, 2023. ISBN: 9780691239262. DOI: doi:10.1515/9780691239262. URL: https://doi.org/10.1515/9780691239262.

[4] Zhanwen Han and Ph Podsiadlowski. "Binary Evolutionary Models". In: *Proceedings of the International Astronomical Union* 4 (May 2008). DOI: 10.1017/S1743921308023193.

[5] Xuefei Chen, Zhengwei Liu, and Zhanwen Han. "Binary stars in the new millennium". In: *Progress in Particle and Nuclear Physics* 134 (2024), p. 104083. ISSN: 0146-6410. DOI: https://doi.org/10.101B6/j.ppnp.2023.104083. URL: https://www.sciencedirect.com/science/article/pii/S0146641023000649.

[6] Marc van der Sluys. *Informatie over sterren, Hoofdstuk 6.2*. CC BY 2.5, via Wikimedia Commons: https://commons.wikimedia.org/w/index.php?curid=804238. 2005. URL: http://hemel.waarnemen.com/Informatie/Sterren/hoofdstuk6.html#h6.2.

[7] Kretschmar, P. et al. "Revisiting the archetypical wind accretor Vela X-1 in depth - Case study of a well-known X-ray binary and the limits of our knowledge". In: *A&A* 652 (2021), A95. DOI: 10.1051/0004-6361/202040272. URL: https://doi.org/10.1051/0004-6361/202040272.

[8] Henny J. G. L. M. Lamers and Joseph P. Cassinelli. *Introduction to Stellar Winds*. 1999.

[9] F. Bernardini et al. "EVENTS LEADING UP TO THE 2015 JUNE OUTBURST OF V404 CYG". In: *The Astrophysical Journal Letters* 818.1 (Feb. 2016), p. L5. DOI: 10.3847/2041-8205/818/1/L5. URL: https://dx.doi.org/10.3847/2041-8205/818/1/L5.

[10] T. Shahbaz et al. "The mass of the black hole in V404 Cygni". In: *Monthly Notices of the Royal Astronomical Society* 271.1 (Nov. 1994), pp. L10–L14. ISSN: 0035-8711. DOI: 10.1093/mnras/271.1.L10. eprint: https://academic.oup.com/mnras/article-pdf/271/1/L10/4002647/mnras271-0L10.pdf. URL: https://doi.org/10.1093/mnras/271.1.L10.

[11] Pešta, Milan and Pejcha, Ondřej. "Mass-ratio distribution of contact binary stars". In: *A&A* 672 (2023), A176. DOI: 10.1051/0004-6361/202245613. URL: https://doi.org/10.1051/0004-6361/202245613.

[12] Riccardo Giacconi et al. "Evidence for x Rays From Sources Outside the Solar System". In: *prl* 9.11 (Dec. 1962), pp. 439–443. DOI: 10.1103/PhysRevLett.9.439.

[13] Francesco Haardt and Laura Maraschi. "X-Ray Spectra from Two-Phase Accretion Disks". In: *apj* 413 (Aug. 1993), p. 507. DOI: 10.1086/173020.

[14] M. Falanga et al. "Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries". In: *Astronomy & Astrophysics* 577 (May 2015), A130. ISSN: 1432-0746. DOI: 10.1051/0004-6361/201425191. URL: http://dx.doi.org/10.1051/0004-6361/201425191.

[15] Janusz Ziółkowski and Andrzej A Zdziarski. "Non-conservative mass transfer in stellar evolution and the case of V404 Cyg/GS 2023+338". In: *Monthly Notices of the Royal Astronomical Society* 480.2 (July 2018), pp. 1580–1586. ISSN: 0035-8711. DOI: 10.1093/mnras/sty1948. eprint: https://academic.oup.com/mnras/article-pdf/480/2/1580/25414517/sty1948.pdf. URL: https://doi.org/10.1093/mnras/sty1948.

[16] Bartolomeo Koninckx, L., De Vito, M. A., and Benvenuto, O. G. "An evolutionary model for the V404 Cyg system". In: *A&A* 674 (2023), A97. DOI: 10.1051/0004-6361/202346571. URL: https://doi.org/10.1051/0004-6361/202346571.

[17] Y. Tanaka and W. H. G. Lewin. "Black hole binaries." In: (Jan. 1995). Ed. by Walter H. G. Lewin, Jan van Paradijs, and Edward P. J. van den Heuvel, pp. 126–174.

[18] Jean-Pierre Lasota. "The disc instability model of dwarf novae and low-mass X-ray binary transients". In: *nar* 45.7 (June 2001), pp. 449–508. DOI: 10.1016/S1387-6473(01)00112-9. arXiv: astro-ph/0102072 [astro-ph].

[19] K Gazeas et al. "Physical parameters of close binary systems: VIII". In: *Monthly Notices of the Royal Astronomical Society* 501.2 (Jan. 2021), pp. 2897–2919. ISSN: 0035-8711. DOI: 10.1093/mnras/staa3753. eprint: https://academic.oup.com/mnras/article-pdf/501/2/2897/35559276/staa3753.pdf. URL: https://doi.org/10.1093/mnras/staa3753.

[20] Gaia Collaboration et al. "Gaia Data Release 2 - Summary of the contents and survey properties". In: *A&A* 616 (2018), A1. DOI: 10.1051/0004-6361/201833051. URL: https://doi.org/10.1051/0004-6361/201833051.

[21] O. Yu. Malkov et al. "A catalogue of eclipsing variables". In: *aap* 446.2 (Feb. 2006), pp. 785–789. DOI: 10.1051/0004-6361:20053137.

[22] N. Morgan, M. Sauer, and E. Guinan. "New Light Curves and Period Study of the Contact Binary W Ursae Majoris". In: *Information Bulletin on Variable Stars* 4517 (Sept. 1997), p. 4.

[23] Tassos Fragos et al. "POSYDON: A General-purpose Population Synthesis Code with Detailed Binary-evolution Simulations". In: *The Astrophysical Journal Supplement Series* 264.2 (Feb. 2023), p. 45. ISSN: 1538-4365. DOI: 10.3847/1538-4365/ac90c1. URL: http://dx.doi.org/10.3847/1538-4365/ac90c1.

[24] The pandas development team. *pandas-dev/pandas: Pandas*. Version latest. Feb. 2020. DOI: 10.5281/zenodo.3509134. URL: https://doi.org/10.5281/zenodo.3509134.

[25] John D. Hunter. "Matplotlib: A 2D Graphics Environment". In: *Computing in Science & Engineering* 9.3 (2007), pp. 90–95. DOI: 10.1109/MCSE.2007.55.

[26] Charles R. Harris et al. "Array programming with NumPy". In: *Nature* 585.7825 (Sept. 2020), pp. 357–362. DOI: 10.1038/s41586-020-2649-2. URL: https://doi.org/10.1038/s41586-020-2649-2.