

Mass Transfer in Binary Star Evolution

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Abstract

In this paper, I will investigate the properties of mass transfer in binary stars, including the Roche Lobe model, evolutionary stages, evolution, rate, progenitors, and resultant stars. I will use the Roche Lobe model to catalyze the stars into Detached (Wind Accretion), Roche Lobe Overflow (RLO), and Contact Binaries (CB). I will then look at stars that fit these stages and investigate them further using data from example systems corroborated with data from POSYDON.

I found that

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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.

Binaries are formed in the same nature of single stars, that being through a molecular cloud molecular clouds. However, due to instability in the formation process, two stars are formed instead of one. [1]

Star's in binary pairs will have a generally have a different evolutionary track then a single star.

It is possible for exoplanets to orbit these

As the binaries evolve, it is possible for the two of them their orbit to eventually collapse, leading to a merger.

1.1 Mass Transfer in Common Binaries

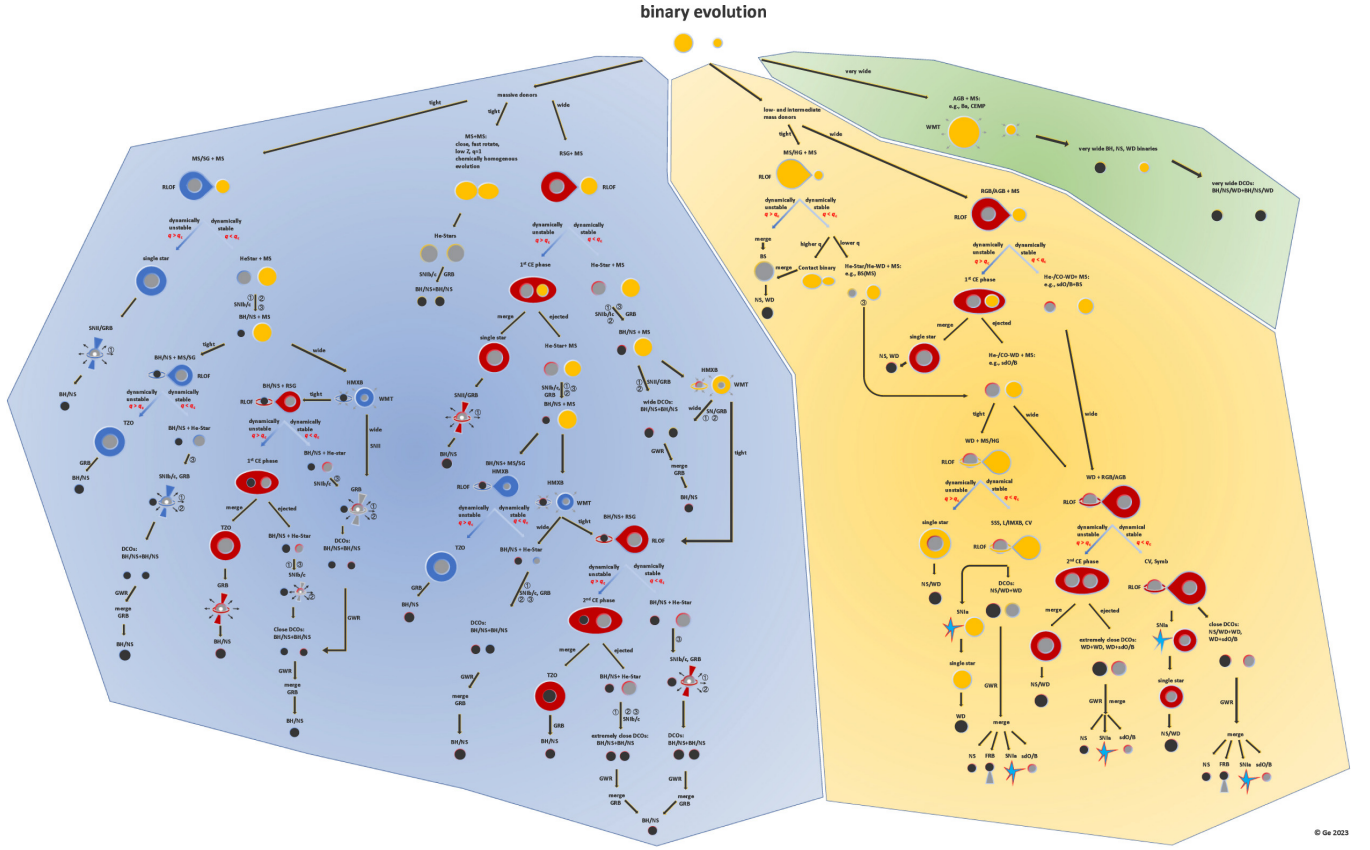
While most systems do not, it is possible in systems with small enough orbital separations and a small enough mass ratio can experience a process called Mass Transfer. Where one star (generally the larger of the two) will "donate" mass to the other star, called the accretor.

It is well known that binary stars can transfer mass, but what are the actual technical details behind it? A large amount of binary stars will exchange mass at some point turning their lifespan [2]

This is incredibly likely to occur at some point during the binaries' lifespan, leading to different evolutionary outcomes then single star evolution.

However, in main sequence systems, (systems where both stars are undergoing the main "stable" period of their life) this process of mass transfer is incredibly hard to detect visually, as the mass transfer between a RG to an MS star will not create an easily observational effect as the energy spike in more extreme examples.

In systems with more extreme stars, for example neutron stars(NS) or black holes(BH), this 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, which can more easily be measured.



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Figure 1: A comprehensive flowchart of various outcomes of binary systems in regard to masses and orbital separations.

Reprint from [2]

1.2 Roche Lobe Model

The Roche Lobe model was discovered by Édouard Roche (cite) and defines the gravitational potential of a binary through a simple model. Simply defined, it defines the region around a star where it can hold onto its mass (i.e. has great enough gravitational potential). If one of the stars in this binary *exceeds* 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).

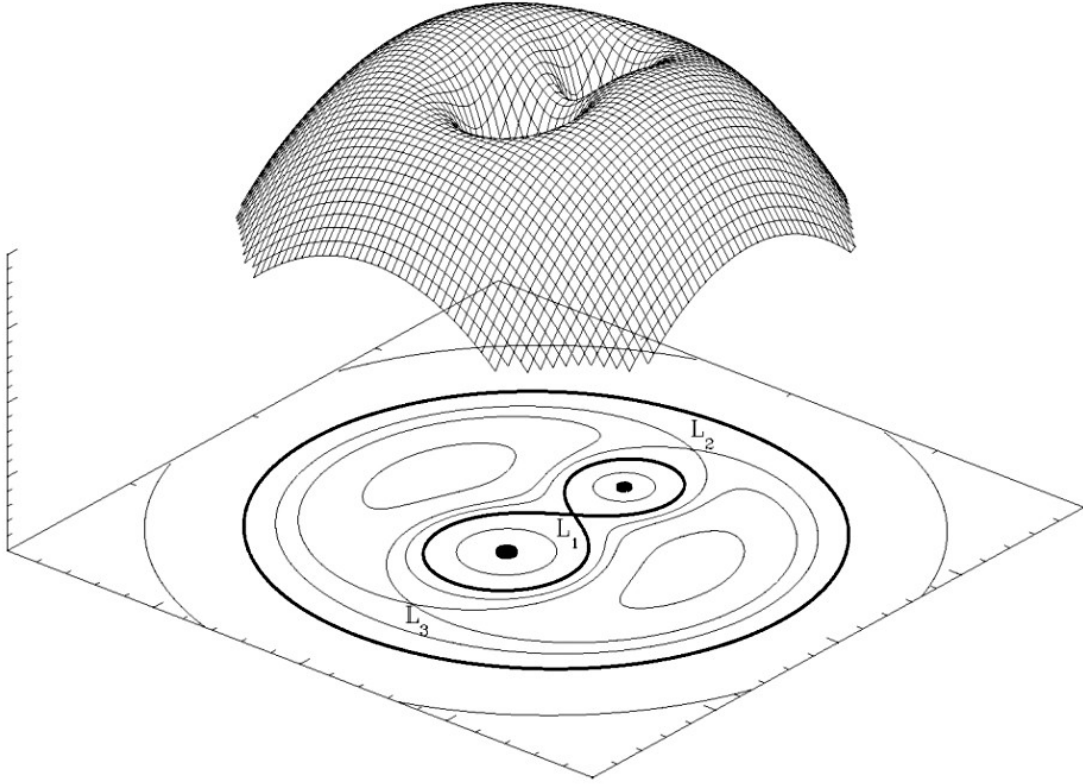


Figure 2: *A 3D representation of the gradient of the Roche lobe*
Reprint from [3]

1.3 Detached

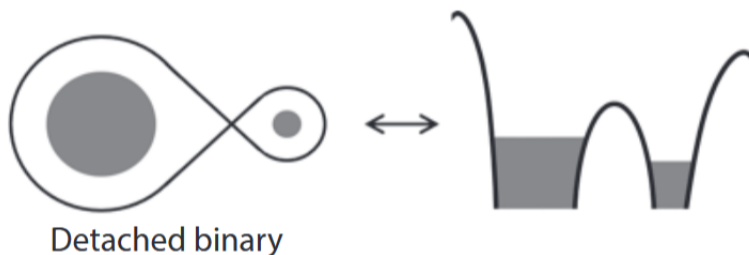
Systems where neither star fills its potential fully are called detached system. In these systems, two stars orbit a COM.

However, in systems which are regarded as detached mass transfer is still possible through a processes called Wind Accretion (see 1.3.1). We see this prominently 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, which we can measure. [3] It is important to note that these systems are not experiencing full-blown RLO, however, they tend to be incredibly close. [3] These systems transfer mass through both wind accretion and in some cases, atmospheric Roche Lobe Overflow.

I used the system Vela X-1 [4] as an example of this, as it is generally regarded as the “archetypical wind accretor” [4]

1.3.1 Wind Accretion Mass Transfer

Wind accretion very different from normal mass transfer in a binary. All stars produce ‘wind’, i.e. mass which is pushed away from the star. This process is called stellar winds, occurring when various types of mass is ejected at speed from the star. All stars have different processes of wind, with some have very high velocities of the wind, and others have lower velocities. [5] In binary stars this process can allow mass to be transferred from one star, to a generally smaller, accretor.



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.*

1.4 Roche Lobe overflow

In systems where one star fills its gravitational potential mass begins to be transferred to its binary partner. This is called Roche Lobe Overflow (RLO) and is defined by a donor and accretor star.

This is incredibly likely to happen at some point in a binaries' lifespan, and it will drastically affect its evolution [2]. Depending on the systems star types, masses, and eccentricity, this process will either be stable or unstable. When this process is unstable, it leads to either the common envelope, which results in either a merger or separation once more. However, if the process of mass transfer is stable, the two stars will remain detached. [2]

In this process, the mass will be transferred through the Lagrange point L_1 , as it is the point of lowest potential between them, as seen in figure 2. [3]

We are able to observe this commonly in X-ray Binaries, where a donor star transferred mass to an accretor which is a compact object (BH or NS). This process then produces X-rays which we can measure to understand the processes within the binary in greater detail.

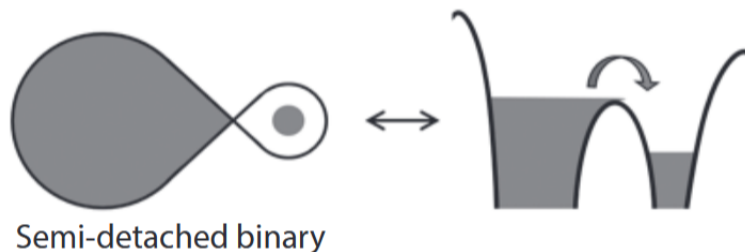


Figure 4: *Reprint from [3]*

I used the system V404 Cygni with data from [6] and [7] as an example of this behavior.

1.5 Contact Binary

In binaries where RLOF occurs it is possible for a star to fill up not just its potential, but the others as well. In cases like these the star then begins to fill up the binaries potential. (i.e. the area above the dark section in figure 5) The system also has a limited potential, and if that fills as well, the system undergoes a stage called “common envelope”

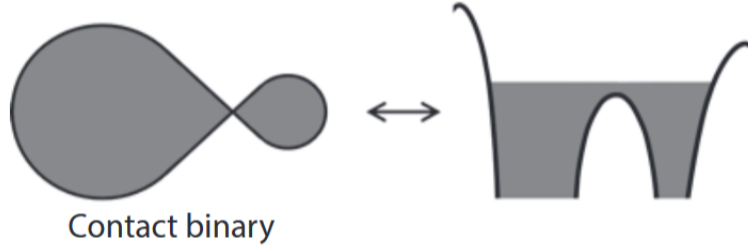


Figure 5: *Reprint from [3]*

This process generally is not stable, as most stars in stage generally are experiencing a stage of their evolution called common envelope (CE). (See section 1.5.1) However, in cases where it is stable, the stars evolve at the same rate, something called “homogenous chemical evolution”. (See fig 1) Contact binaries generally have very little to no eccentricity, as their close orbits self stabilize. [3]

1.5.1 Common Envelope

In the CE stage of binary evolution there are two distinct outcomes, both of which heavily depend on the systems initial conditions. These are that the two stars merge, becoming a single star, or that one star is ejected.

In this process the potential of the systems is completely filled, at which point mass stars being pushed out of the system through L_2 . This mass then begins to form a pseudo disk around the stars, orbiting a slower rate [3]. This leads to be This mass may be fully ejected from the system entirely, creating ionized gas around the stars, [3]which can be observed from earth.

1.5.2 Stable Evolution

In systems where mass transfer is not happening and both of the stars are at stable points in their evolution (i.e. both MS), the stars will share their mass. This means that their “shells” will evolve in tandem.

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

2.1.1 Known properties

	Vela X-1 A	Vela X-1 B
Star Type	Neutron Star	Supergiant [4]
Masses M_{\odot}	≥ 1.8 [4]	20–30 [4]
Radius	11–12.5 $_{KM}$ [4]	30 R_{\odot} [4]
Separation	2 kpc [4]	
Mass Loss Rate	$10^{-6}M_{\odot}yr^{-1}$ [4]	
Eccentricity	$e \approx 0.0898$) [4]	

Table 1: *Properties of Vela X-1*

1.6 X-ray Binaries

1.6.1 X-rays in accretion

1.6.2 Low Mass X-ray Binaries (LMXBS)

1.6.3 High Mass X-ray Binaries (HMXBS)

Data Acquisition

2.1 Vela X-1 (Detached)

Vela X-1 consists of a Neutron Star and Supergiant and is an Eclipsing and pulsing HMXB (sect. 1.6.3). This means that the Neutron star passed behind the Supergiant every 8.94 days [8], leading to a variable luminosity between $10^{36} \text{ erg s}^{-1}$ and $10^{37} \text{ erg s}^{-1}$. Additionally, the neutron star itself is spinning every 293 seconds. [4].

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 its broadband spectra. Astronomers use Vela X-1 as examples when looking at other systems with comparable x-ray emissions. [4]

The wind accretion (see 1.3.1) comes in the form of wind from 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 [4], 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.

	W UMa A	W UMa B
Masses M_{\odot}	$1.139 \pm 0.019[9]$	$0.551 \pm 0.006[9]$
Radius R_{\odot}	$1.092 \pm 0.016[9]$	$0.792 \pm 0.015[9]$
Temperature K	$6450 \pm 100 [9]$	$6170 \pm 21 [9]$
Luminosity L_{\odot}	$1.557 \pm 0.166[9]$	$0.978 \pm 0.071[9]$
Distance	$52pc [10]$	
Max Magnitude	$7.75 [11]$	
Min Magnitude	$8.48 [11]$	
Period	$.3336 \text{ days } [9]$	
Inclination Plane	$88.4 \pm 0.8^{\circ} [9]$	

Table 2: *Properties of W Ursae Majoris*

2.1.2 Notes

Vela X-1A has a mass defined to be higher than the Chandrasekar limit, which allows it to be used to help create models for compact stars and equations-of-state. [4]

2.2 W Ursae Majoris (Contact Binary)

2.2.1 Known properties

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 it has a high magnitude at 7.75 at peak and 8.48 at minimum (table 2), 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. 6). This magnitude variability is due to the fact that the binary is eclipsing due to its low inclination plane (table 2), meaning that one of the stars will pass behind the other in its 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.

	V404 Cygni B (Donor)	V404 Cygni A (Black Hole)
Star Type	Early K-type Giant	Black Hole
Masses	$.7 M_{\odot}$ [6]	$9 M_{\odot}$ [7]
Radius	$6.0 R_{\odot}$ [7]	
Temperature	$4800 K$ [7]	
Luminosity	$10.2 L_{\odot}$ [7]	
Distance	2390_{pc} [6]	

Table 3: *Properties of V404 Cygni*

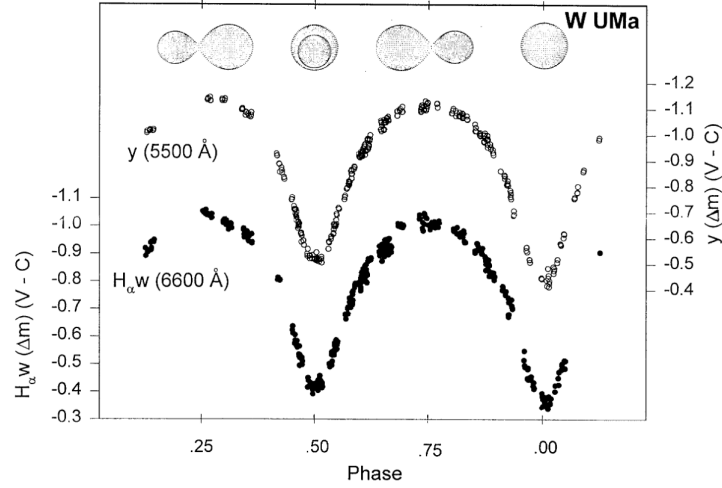


Figure 6: *Reprint from [12]*

2.3 Roche Lobe overflow in V404 Cygni

2.3.1 Known properties

V404 is a LMXB (sect 1.6.2), 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, greatly increasing the luminosity of the system.

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*

2.4 POSYDON Simulations

I used data generated by POSYDON [13] 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 utilizes 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 ≈ 6.1 million 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. 7)

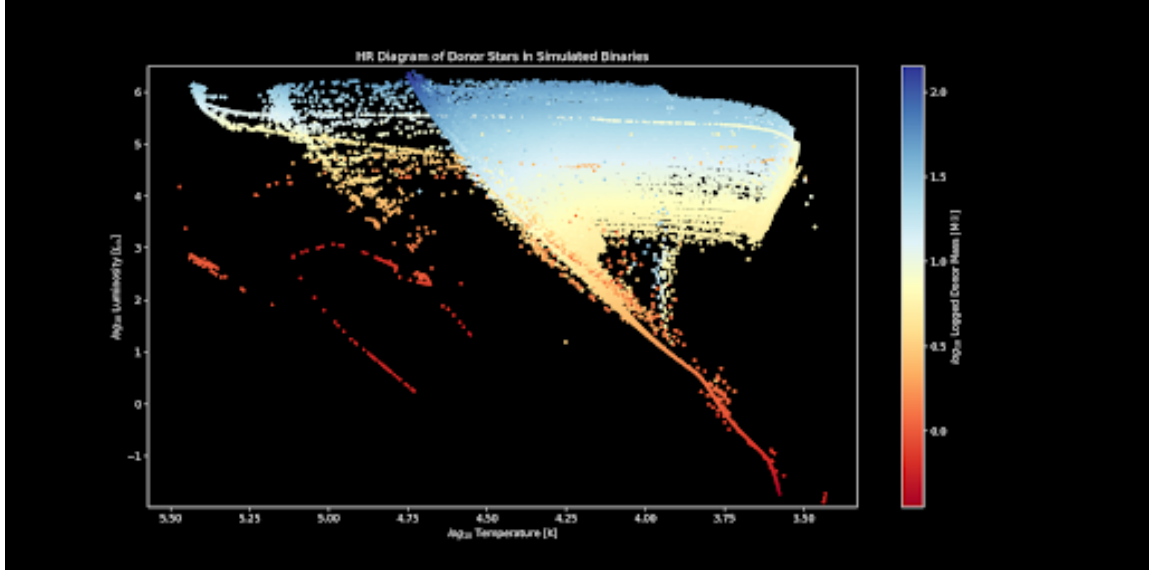


Figure 7: *HR Diagram of the donor star for the full POSYDON dataset. Note that the color of the plotted points correspond to the \log_{10} mass of the donor star. Generated with Matplotlib*

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 [14], Matplotlib [15], and NumPy [16]. 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 Roche Lobe Overflow

Full-blown RLO occurs in both all types of XrB's, including HMXBs and LMXBs, however, it is more common in LMXBs.

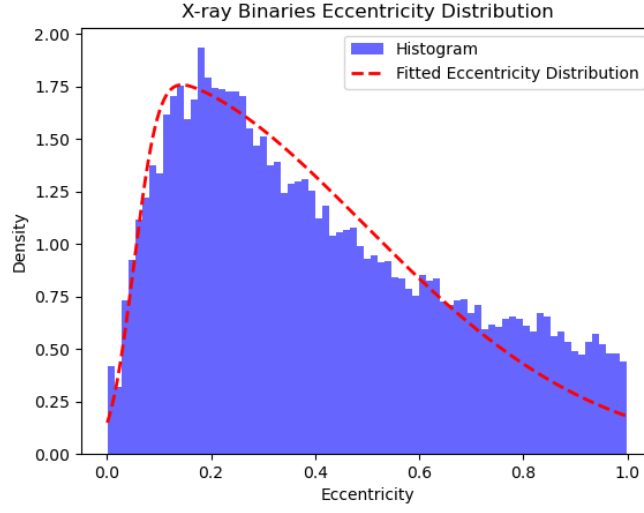


Figure 8: *Eccentricity distribution of X-ray Binaries*

In figure 8 we can see that x-ray binaries have a standard Gaussian distribution, with a peak at around $\approx .24$

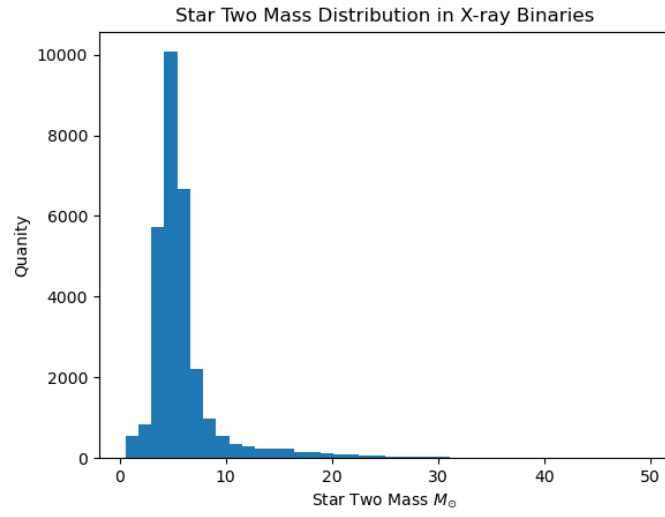


Figure 9: *Mass distribution of X-ray Binaries*

In figure 9 we see that the majority of X-ray binaries masses are centered around ≈ 5.5

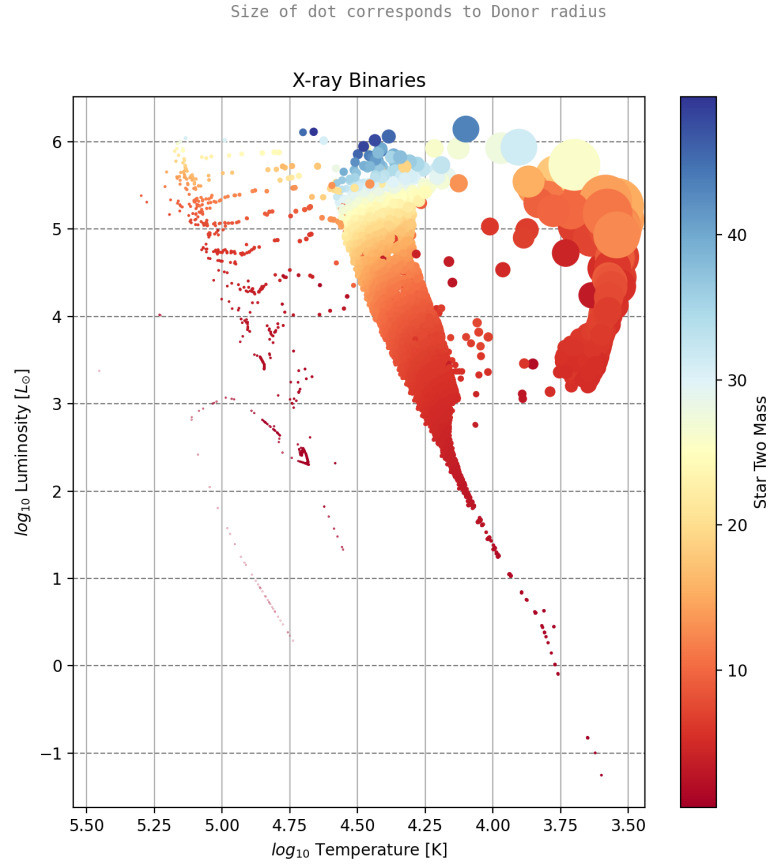


Figure 10: *HR diagram of the donor star in X-ray Binaries*

In figure 10 we can see that X-ray binaries' donor stars generally follow a semi-standard HR diagram

3.1.1 V404 Cygni Results

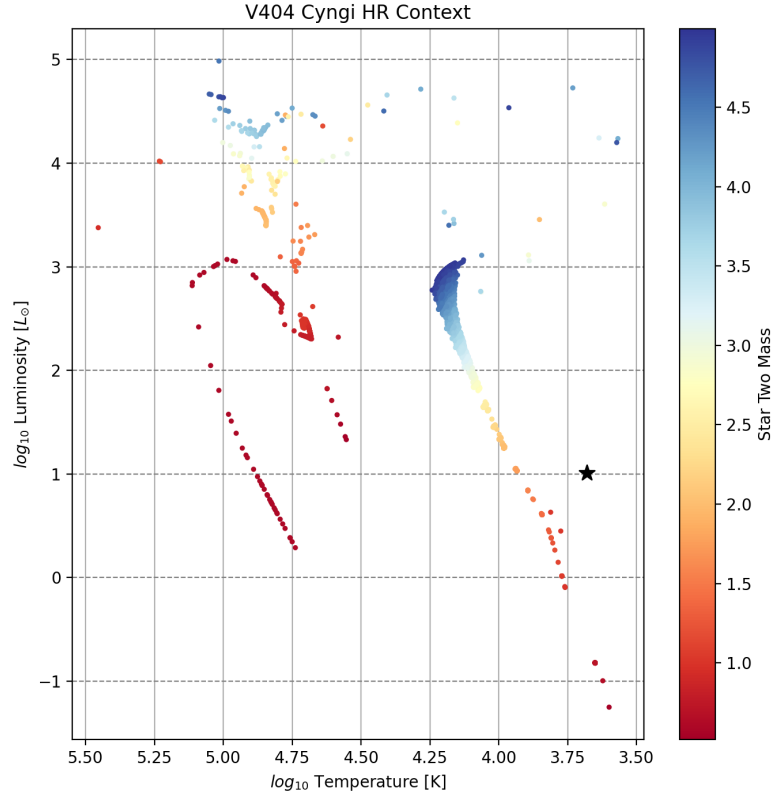


Figure 11: *HR Diagram with reference for V404 Cygni*

I discovered that does not fall onto the two main simulated evolutionary tracks for LMXBs. See section 4.1

3.2 Contact Binaries

Through my analysis I discovered that contact binaries had some of the most interesting results.

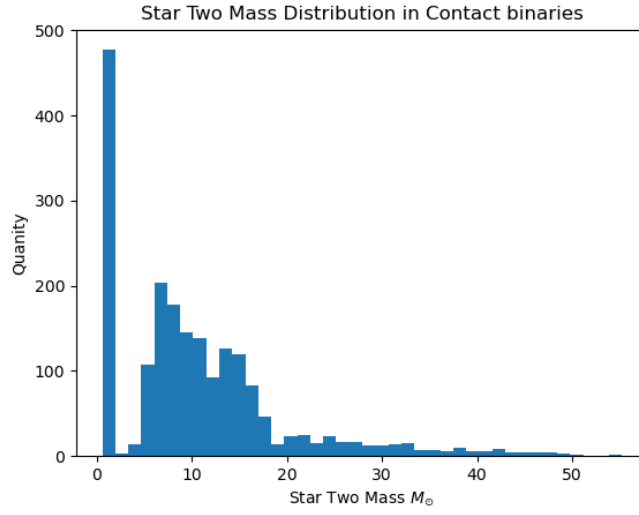


Figure 12: *Eccentricity distribution of contact Binaries*

In figure 12 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.

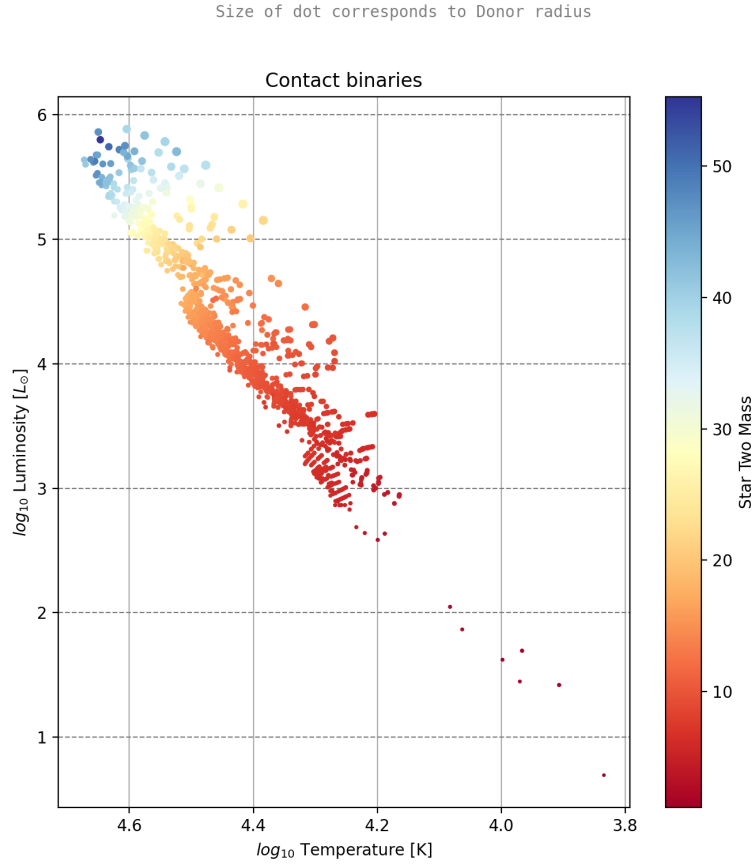


Figure 13: *HR diagram of contact Binaries*

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.

3.2.1 W UMa Cygni Results

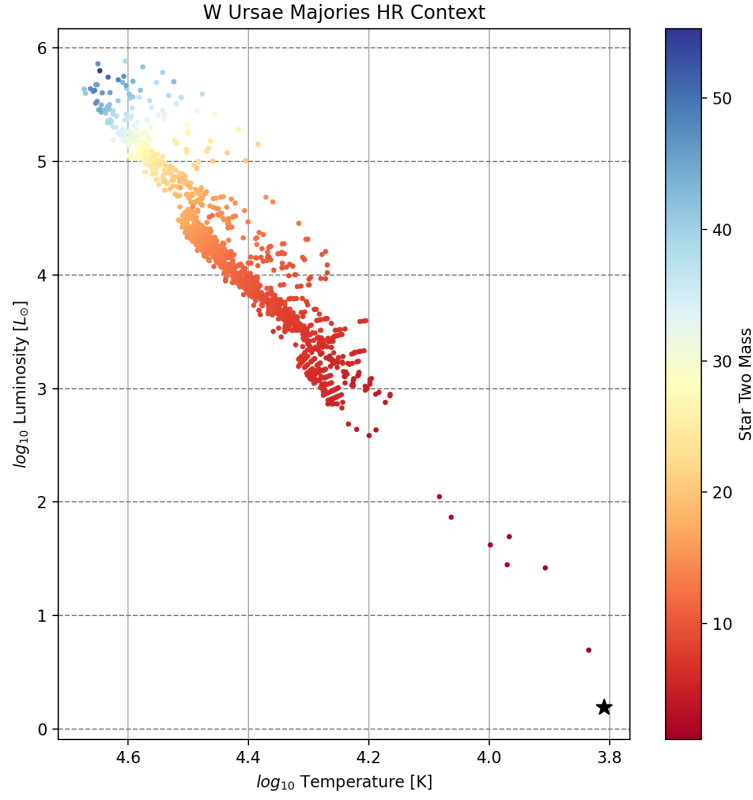


Figure 14: *HR Diagram with reference for W UMa using W UMa A*

In figure 14 we see that W UMa also follows this linear relationship, however, it has a much lower temperature and luminosity than most of the population.

3.3 Detached Binaries

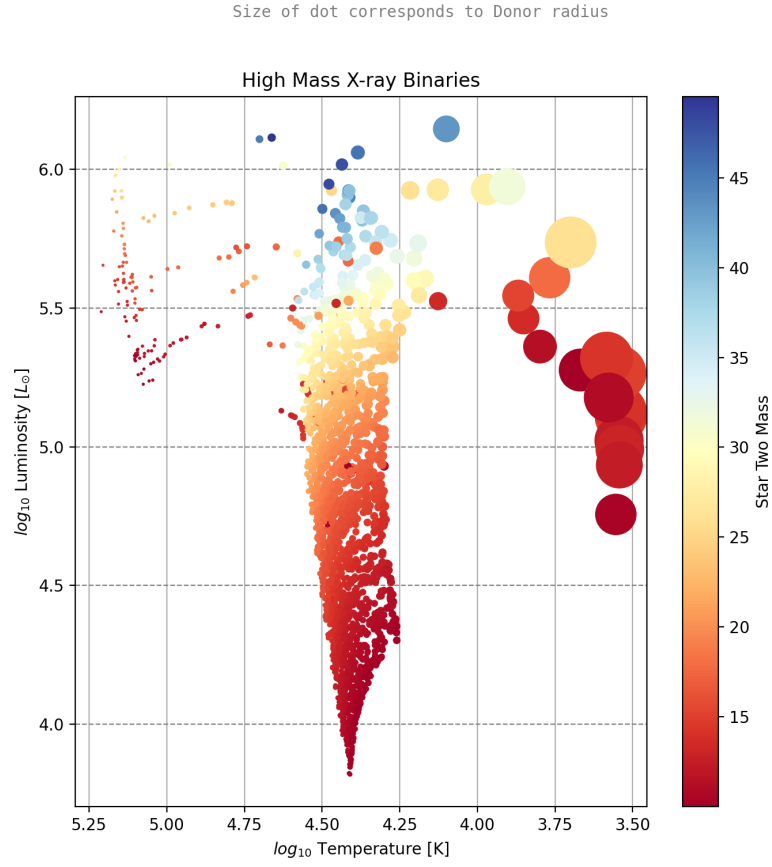


Figure 15: *HR Diagram with of HMXBs*

3.3.1 Vela X-1 Results

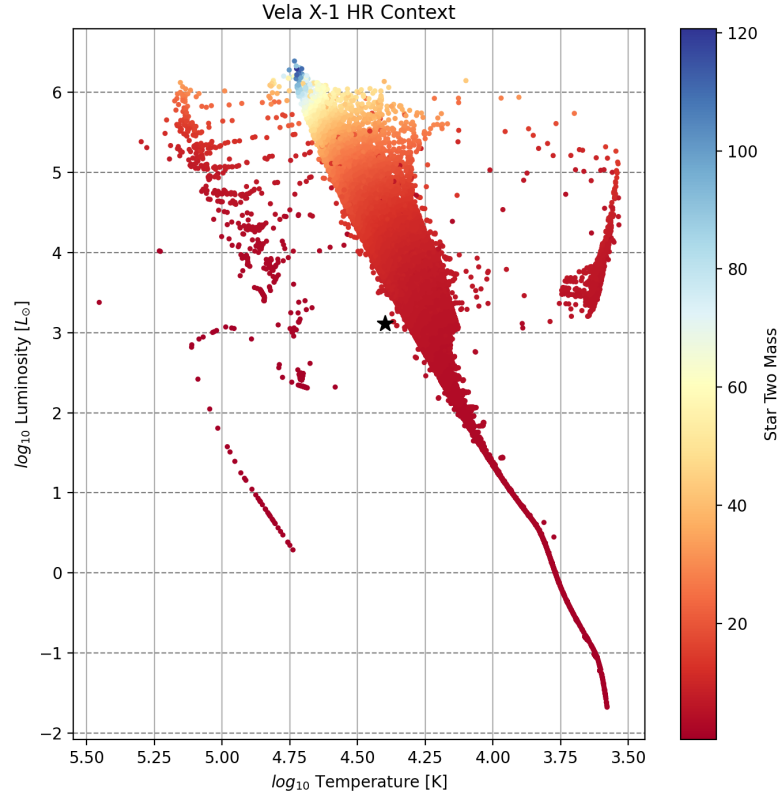


Figure 16: *HR Diagram with reference for Vela X-1*

In figure 16 we can see that Vela X-1 Falls into a very normal location for main sequence stars.

Conclusion

In conclusion mass transfer heavily affects the evolution of binary stars, leading them to evolve in a

4.1 V404 Cyngi

There are a lot of different reasons why this could be, including mass transfer limiting the luminosity, error, etc.

4.2 W UMa Cyngi

4.3 Vela X-1 Cyngi

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.

5.1 Git Galore

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.

Sources

1. Offner, S. S. R., Dunham, M. M., Lee, K. I., Arce, H. G. & Fielding, D. B. THE TURBULENT ORIGIN OF OUTFLOW AND SPIN MISALIGNMENT IN MULTIPLE STAR SYSTEMS. *The Astrophysical Journal Letters* **827**, L11. <https://dx.doi.org/10.3847/2041-8205/827/1/L11> (Apr. 2016).
2. Chen, X., Liu, Z. & Han, Z. Binary stars in the new millennium. *Progress in Particle and Nuclear Physics* **134**, 104083. ISSN: 0146-6410. <https://www.sciencedirect.com/science/article/pii/S0146641023000649> (2024).
3. Tauris, T. M. & van den Heuvel, E. P. *From Stars to X-ray Binaries and Gravitational Wave Sources* ISBN: 9780691239262. <https://doi.org/10.1515/9780691239262> (Princeton University Press, Princeton, 2023).

4. 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. *A&A* **652**, A95. <https://doi.org/10.1051/0004-6361/202040272> (2021).
5. Lamers, H. J. G. L. M. & Cassinelli, J. P. *Introduction to Stellar Winds* (1999).
6. Bernardini, F. *et al.* EVENTS LEADING UP TO THE 2015 JUNE OUTBURST OF V404 CYG. *The Astrophysical Journal Letters* **818**, L5. <https://dx.doi.org/10.3847/2041-8205/818/1/L5> (Feb. 2016).
7. Shahbaz, T. *et al.* The mass of the black hole in V404 Cygni. *Monthly Notices of the Royal Astronomical Society* **271**, L10–L14. ISSN: 0035-8711. eprint: <https://academic.oup.com/mnras/article-pdf/271/1/L10/4002647/mnras271-0L10.pdf>. <https://doi.org/10.1093/mnras/271.1.L10> (Nov. 1994).
8. Falanga, M. *et al.* Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries. *Astronomy & Astrophysics* **577**, A130. ISSN: 1432-0746. <http://dx.doi.org/10.1051/0004-6361/201425191> (May 2015).
9. Gazeas, K. *et al.* Physical parameters of close binary systems: VIII. *Monthly Notices of the Royal Astronomical Society* **501**, 2897–2919. ISSN: 0035-8711. eprint: <https://academic.oup.com/mnras/article-pdf/501/2/2897/35559276/staa3753.pdf>. <https://doi.org/10.1093/mnras/staa3753> (Jan. 2021).
10. Gaia Collaboration *et al.* Gaia Data Release 2 - Summary of the contents and survey properties. *A&A* **616**, A1. <https://doi.org/10.1051/0004-6361/201833051> (2018).
11. Malkov, O. Y., Oblak, E., Snegireva, E. A. & Torra, J. A catalogue of eclipsing variables. *aap* **446**, 785–789 (Feb. 2006).
12. Morgan, N., Sauer, M. & Guinan, E. New Light Curves and Period Study of the Contact Binary W Ursae Majoris. *Information Bulletin on Variable Stars* **4517**, 4 (Sept. 1997).
13. Fragos, T. *et al.* POSYDON: A General-purpose Population Synthesis Code with Detailed Binary-evolution Simulations. *The Astrophysical Journal Supplement Series* **264**, 45. ISSN: 1538-4365. <http://dx.doi.org/10.3847/1538-4365/ac90c1> (Feb. 2023).
14. Pandas development team, T. *pandas-dev/pandas: Pandas version latest*. Feb. 2020. <https://doi.org/10.5281/zenodo.3509134>.
15. Hunter, J. D. Matplotlib: A 2D Graphics Environment. *Computing in Science & Engineering* **9**, 90–95 (2007).

16. Harris, C. R. *et al.* Array programming with NumPy. *Nature* **585**, 357–362.
<https://doi.org/10.1038/s41586-020-2649-2> (Sept. 2020).