Mass Transfer in Binary Star Evolution

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April 5, 2025

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 ... and ...

*Mentored by Joseph DalSanto

Introduction

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 (cite)

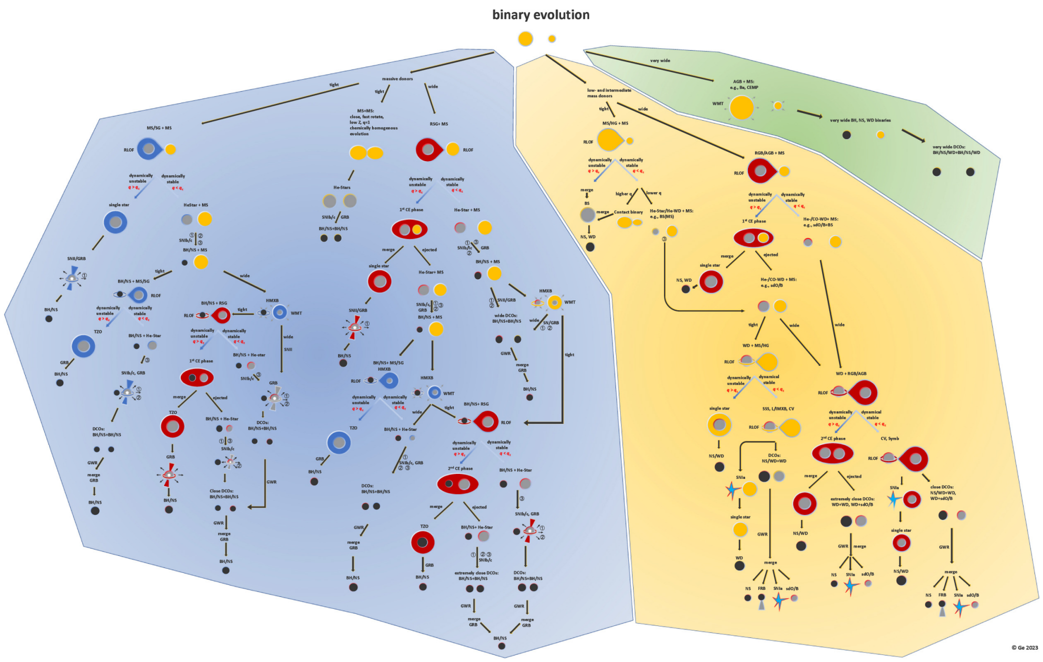
1.1 Mass Transfer in Common Binaries

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 these stars is called a binary. These systems are incredibly important, as they allow us to see how stars in different stages of evolution interact with others.

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 (typically the larger of the two) will "donate" mass to the other star, typically called an accretor.

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.

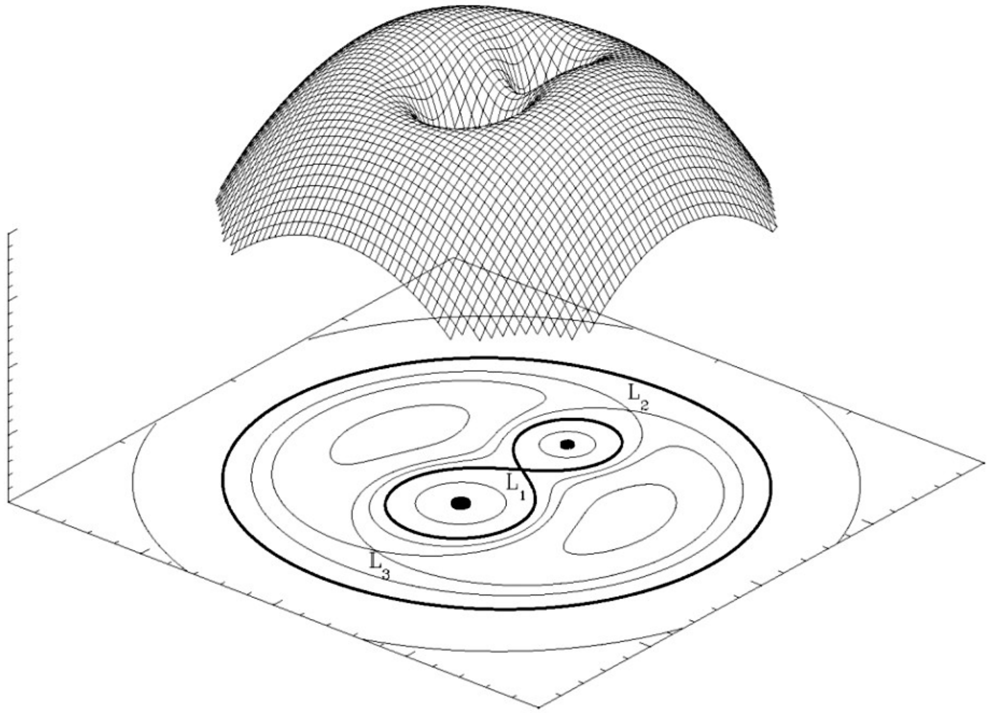
In systems with more extreme stars, for example neutron stars or black holes, this process of mass transfer leads to much more pronounced effects. This is because as the mass is transferred to the BH or NS the process leads to a large spike in X-ray emissions, which can be easily measured.



Reprint from

1.2 Roche Lobe Model

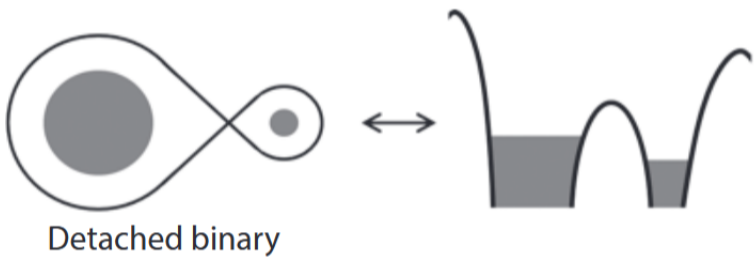
The Roche Lobe model was discovered by Édouard Roche (cite) and defines the gravitational potential of a binary through a simple model. Simply defined, it defines the region around a star where it can hold onto it mass (ie has great enough gravitational potential). If one of the stars in this binary *exceeds* said lobe, it will transfer mass to its binary pair. Is this interaction the star getting rid of its mass is called the **Donor** and the star receiving mass is called the **Accretor**. 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).



1.3 Detached

In systems which are regarded as detached, i.e., neither star has filled its Roche Lobe mass transfer is still possible through a processed called Wind Accretion. 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. [8] It is important to note that these systems are not experiencing full-blown RLO, however, they tend to be incredibly close. [8] This systems transfer mass through both wind accretion and in some cases, atmospheric RLO.

I used the system Vela X-1 [6] as a example of this, as it is generally regarded as the "archetypical wind accretor" [6]

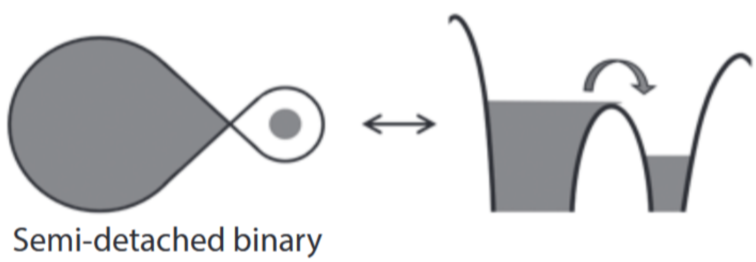


reprint from [8]

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.

We see this commonly in X-ray Binaries, where a donor star transferred mass to an accretor which is a compact object (either a neutron star (NS) or black hole (BH). This process then produces X-rays which we can measure to understand the processes within the binary in greater detail. This process is generally ***directly*** in RLO through L_1.

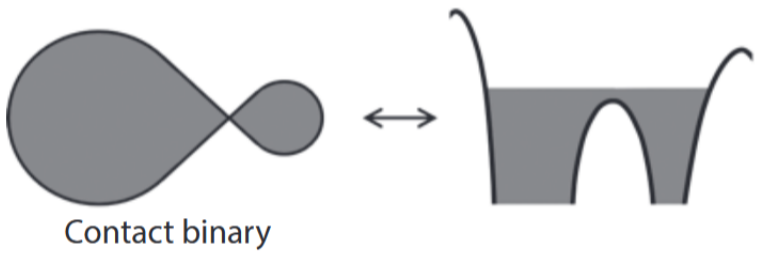


reprint from [8]

I used the system V404 Cyngi with data from [2] and [7] as an example of this behavior.

1.5 Contact Binary

A Contact Binary occursz when both stars fill their potential and start filling up their systems potential, this leads to the sharing mass.



reprint from [8]

It is important to note that these contact binaries appear to be elongated towards each other.

Smth smth smth

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.

Data Acquisition

2.1 Vela X-1 (Detached)

2.1.1 Observed

	Vela X-1 A	Vela X-1 B
Star Type	Neutron Star	Supergiant [6]
Masses$M_\odot$	≥ 1.8 [6]	20–30 [6]
Radius	11-12.5$_{KM}$ [6]	30 $M_\odot$ [6]

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 [3], 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. [6]. Vela X-1 is described as an archetypical wind accretor. This is because unlike some systems... (ie [6])

2.1.2 Simulated

Simulated data is good because of xyz and is useful because of xyz. data was made using xyz

2.2 W Ursae Majoris (Contact Binary)

2.2.1 Observed

	W UMa A	W UMa B
Star Type	O-Type [1]	O-Type [1]
Masses$M_\odot$	1.139 ± 0.019[5]	0.551 ± 0.006[5]
Radius$R_\odot$	1.092 ± 0.016[5]	0.792 ± 0.015[5]
Temperature$K$	33750 [1]	33500 [1]
Luminosity$L_\odot$	1.557 ± 0.166[5]	0.978 ± 0.071[5]

2.2.2 Simulated

Simulated data is good because of xyz and is useful because of xyz. data was made using xyz

2.3 Roche Lobe overflow in V404 Cyngi

2.3.1 Observed

	V404 Cyngi B (Donor)	V404 Cyngi A (Black Hole)
Star Type	Early K-type Giant	Black Hole
Masses$M_\odot$	.7 [2]	9 [7]
Radius$R_\odot$	6.0 [7]	
Temperature$K$	4800 [7]	
Luminosity$L_\odot$	10.2 [7]	

Observed data of V404 Cyngi shows the mass of the black hole is $9M_\odot$. The Donar star properties

2.3.2 Simulated

Simulated data is good because of xyz and is useful because of xyz. data was made using xyz

2.4 POSYDON Simulations

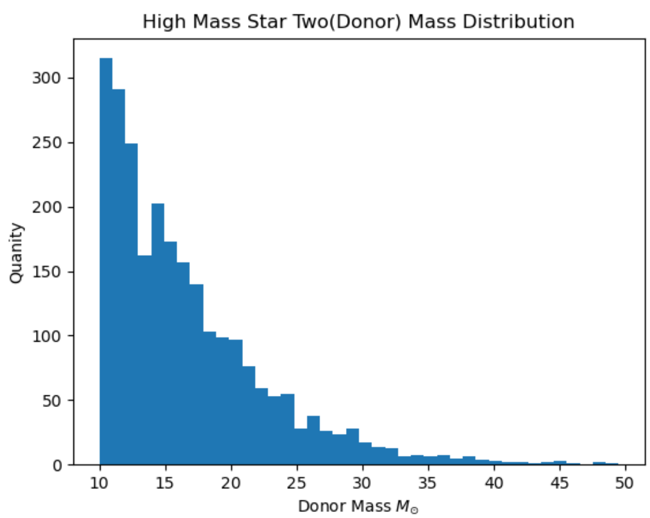
I used data generated by POSYDON [4] in corroboration with three observed systems in order to fully understand the depth of the process of mass transfer in Binary Systems. [8]

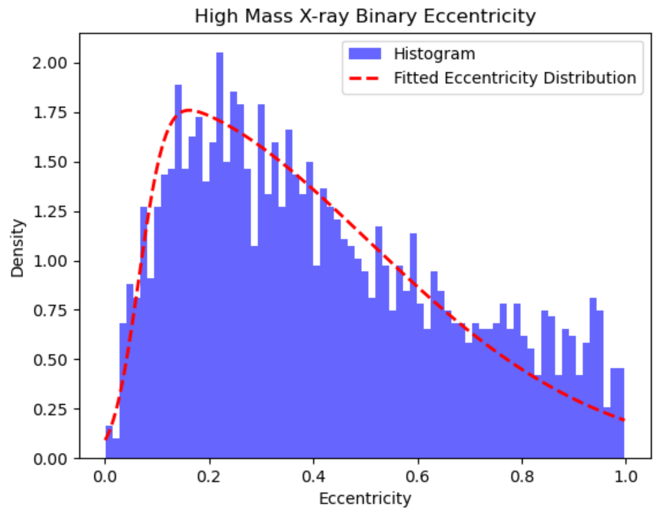
Results

Through my research I found these distinct types of evolutionary processes ... and their stages of evolution, causes and populations.

3.1 Detached

In detached binaries, there is still the possibility for mass transfer. These systems are typically called HMXBs. I found that these systems have a distribution as pictured. Note these systems are only ones with full blown RLO due to simulation of WA constraints





Additionally, HMXBs fall in this region on the HR diagram

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Size of dot corresponds to Donor radius
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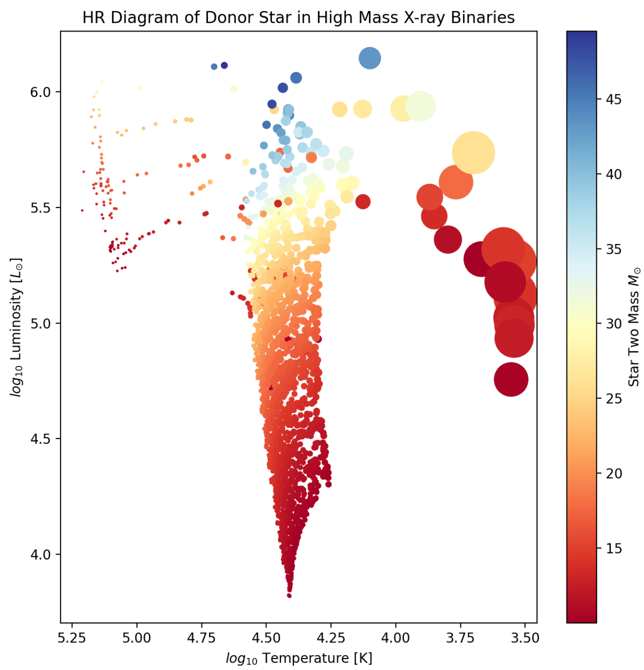
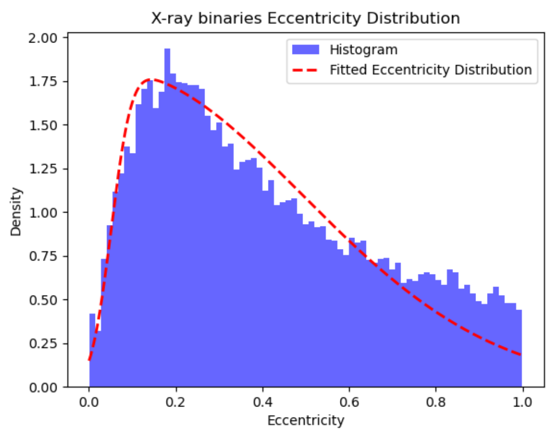
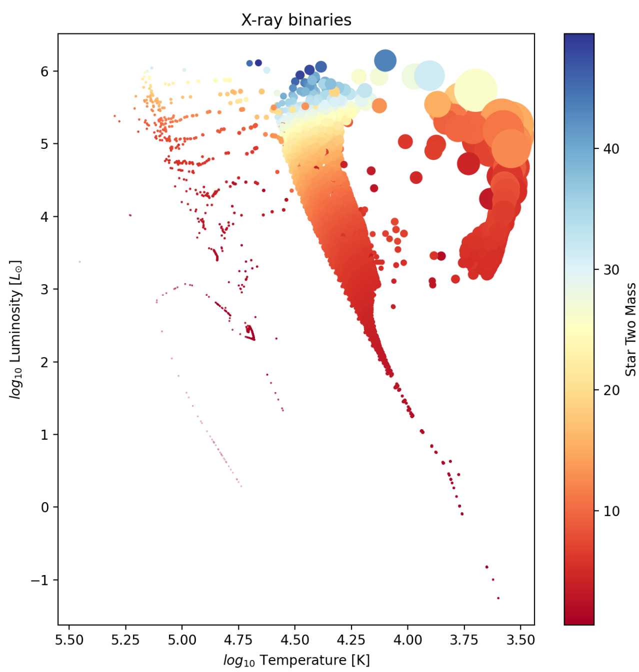


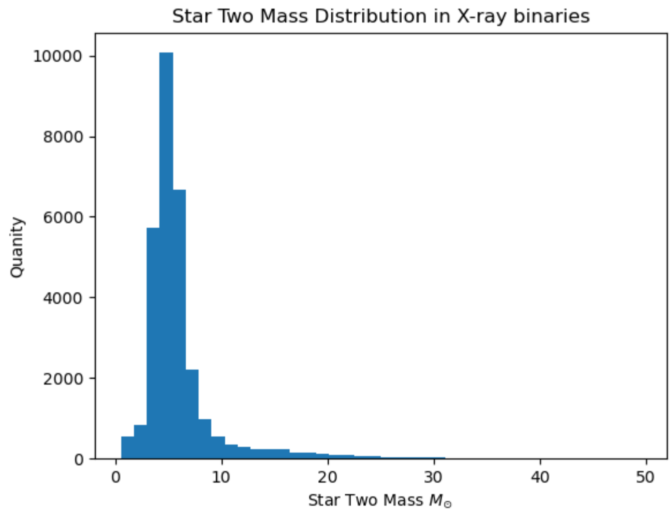
3.2 Roche Lobe Overflow

Full blown RLO occurs in both all types of XrB's, including both HMXBs and LMXBs. This systems



Size of dot corresponds to Donor star radius



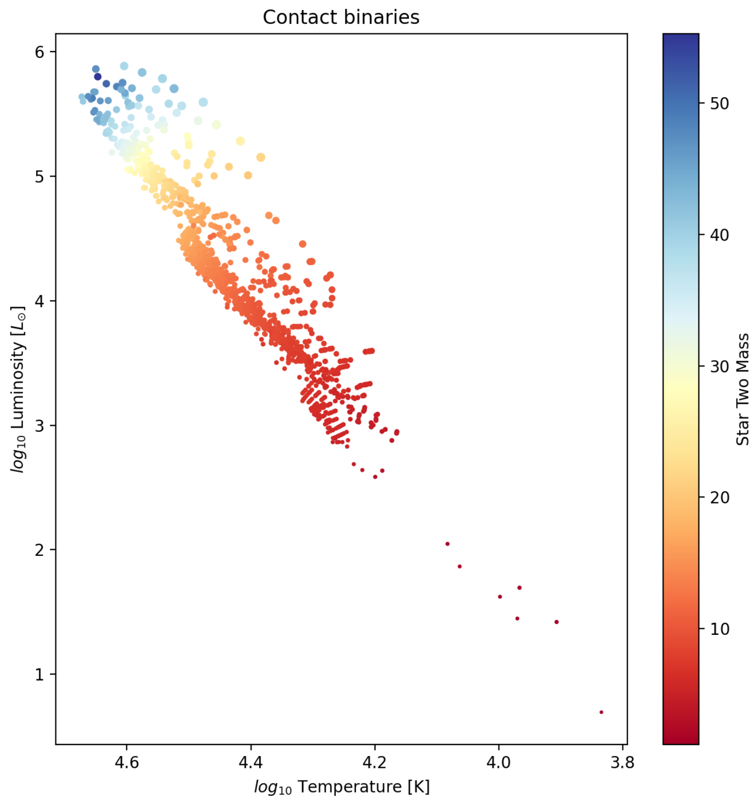


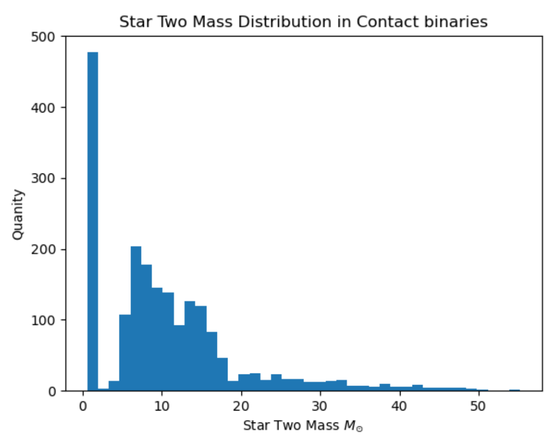
(cite and insert figs)

3.3 Contact Binary

I found that in CE systems this can happen with these evolutionary changes. We see an example in observed systems (insert source and figs) in our POSYDON [4] simulated data too. (figs)

Size of dot corresponds to Donor star radius





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.

4.1 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.

Conclusion

In conclusion mass transfer effects binary systems in these ways, which can lead to these evolutionary outcomes.

Sources

[1] E.A. Antokhina, M. Srinivasa Rao, and M. Parthasarathy. "Light curve analysis of Hipparcos data for the massive O-type eclipsing binary UW CMa". In: *New Astronomy* 16.3 (Apr. 2011), pp. 177–182. ISSN: 1384-1076. DOI: `10.1016/j.newast.2010.09.008`. URL: `http://dx.doi.org/10.1016/j.newast.2010.09.008`.

[2] 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`.

[3] 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`.

[4] 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`.

[5] 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`.

[6] 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`.

[7] 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`.

[8] 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`.