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 ... and ...

*Mentored by Joseph DalSanto

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. [8]

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 [3]

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.

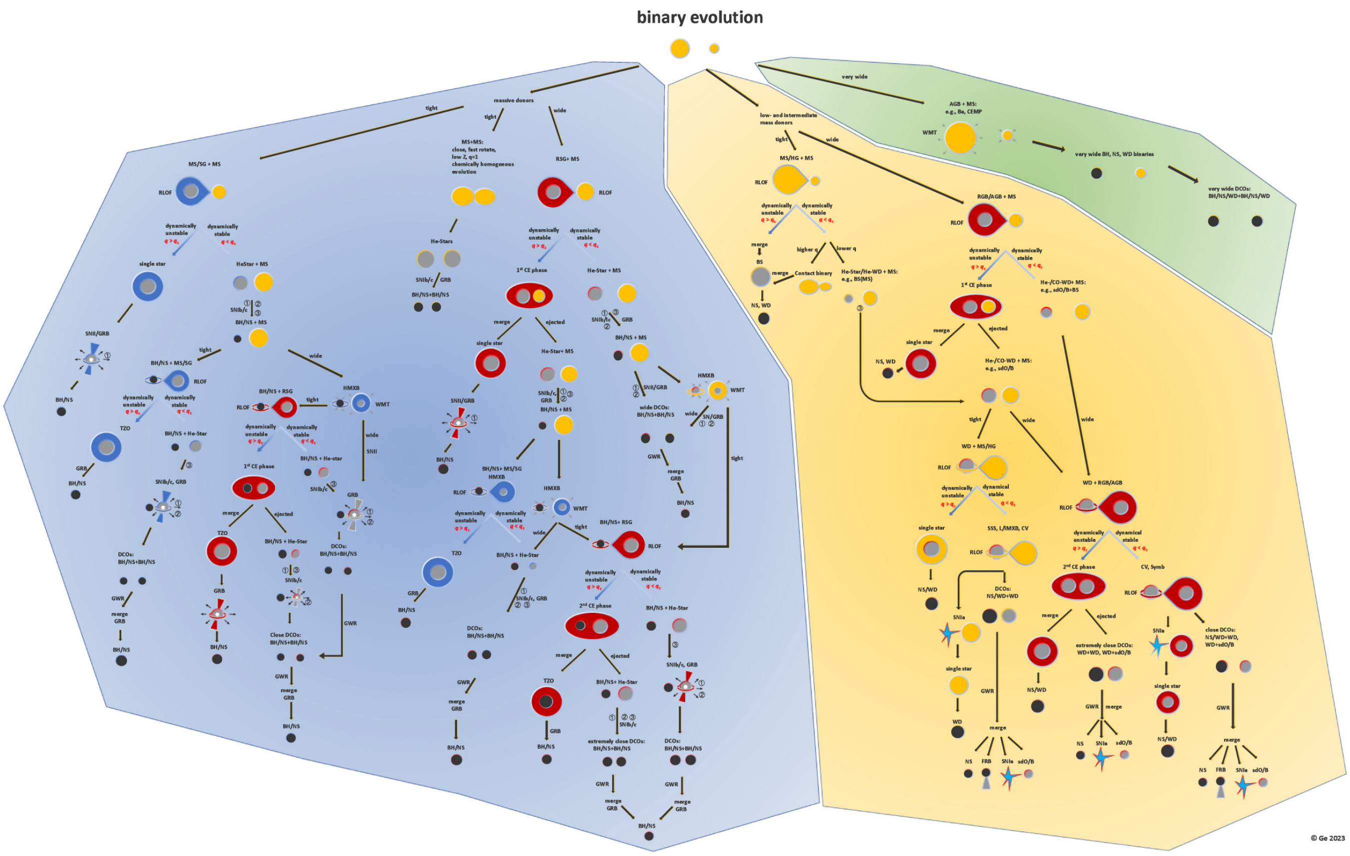


Figure 1: A comprehensive flowchart of various outcomes of binary systems in regard to masses and orbital separations.

Reprint from [3]

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. 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).

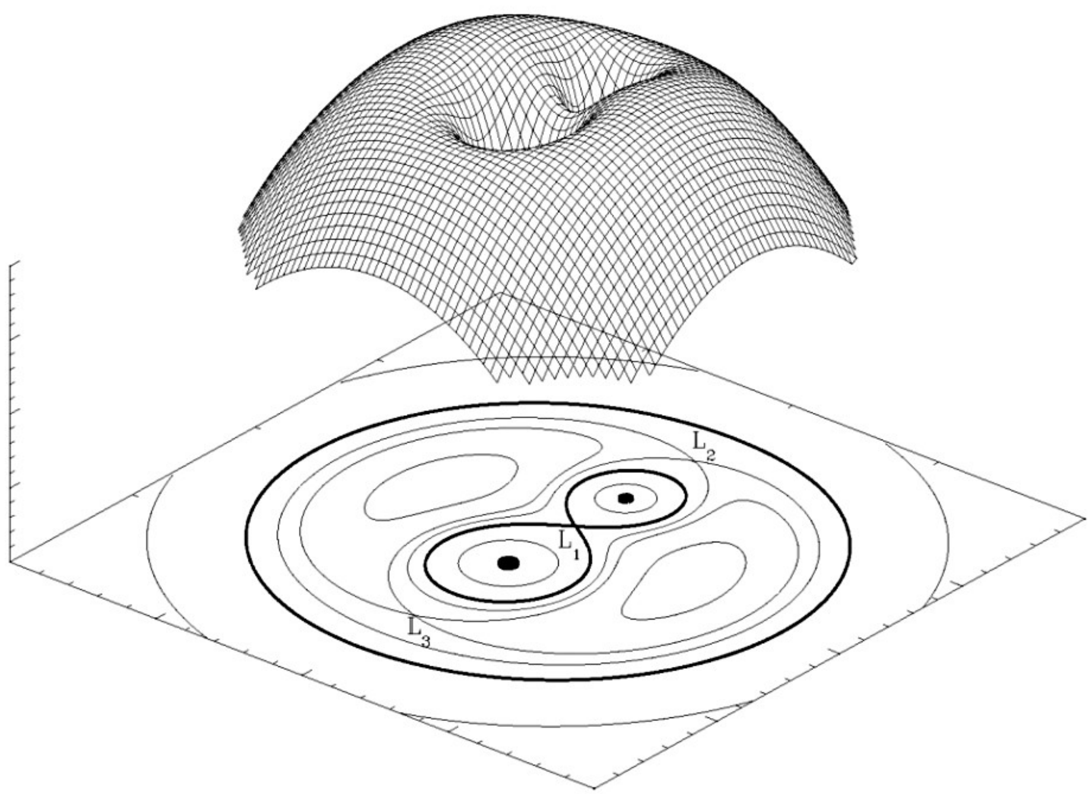


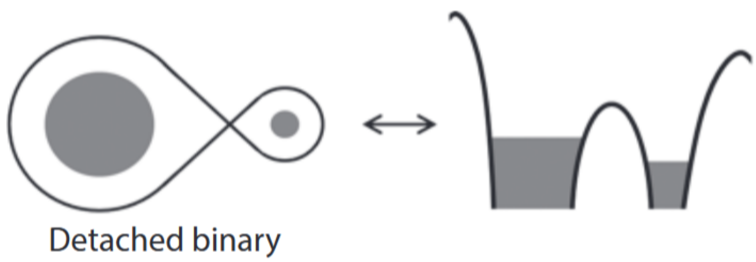
Figure 2: A 3D representation of the gradient of the Roche lobe
Reprint from [10]

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. 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. [10] It is important to note that these systems are not experiencing full-blown RLO, however, they tend to be incredibly close. [10] These systems transfer mass through both wind accretion and in some cases, atmospheric Roche Lobe Overflow.

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



Reprint from [10]

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 [3]. Depending on the systems star types, masses, and eccentricity, this process will either be stable or unstable. When this process if 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. [3]

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. [10]

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.

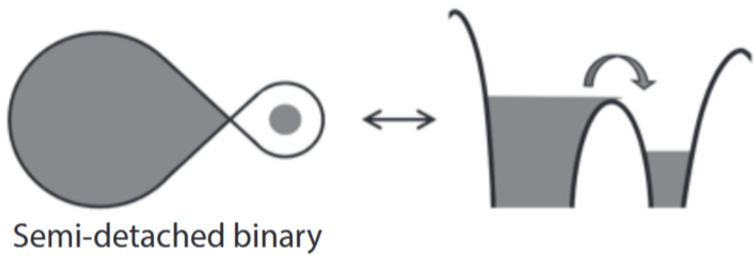


Figure 4: *Reprint from [10]*

I used the system V404 Cyngi with data from [2] and [9] 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"

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. [10]

1.5.1 Unstable Evolution

During a binaries lifetime it is likely for one of the stars to become

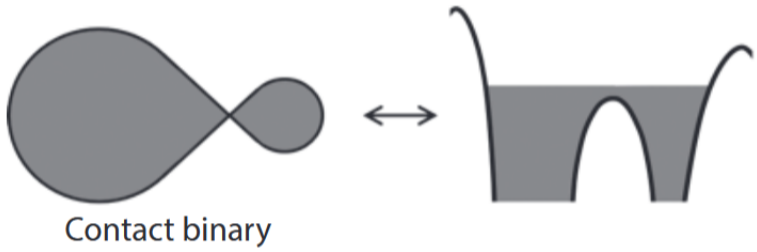


Figure 5: *Reprint from [10]*

1.5.2 Stable Evolution

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 [7]
Masses$M_\odot$	≥ 1.8 [7]	20–30 [7]
Radius	11-12.5$_{KM}$ [7]	30 $M_\odot$ [7]

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 [4], 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. This is because unlike some systems... (ie [7])

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[6]	0.551 ± 0.006[6]
Radius$R_\odot$	1.092 ± 0.016[6]	0.792 ± 0.015[6]
Temperature$K$	33750 [1]	33500 [1]
Luminosity$L_\odot$	1.557 ± 0.166[6]	0.978 ± 0.071[6]

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 [9]
Radius$R_\odot$	6.0 [9]	
Temperature$K$	4800 [9]	
Luminosity$L_\odot$	10.2 [9]	

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

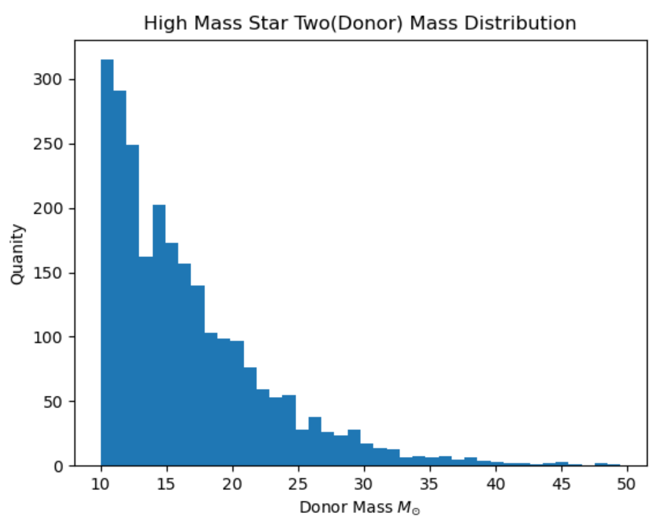
I used data generated by POSYDON [5] in corroboration with three observed systems in order to fully understand the depth of the process of mass transfer in Binary Systems. [10]

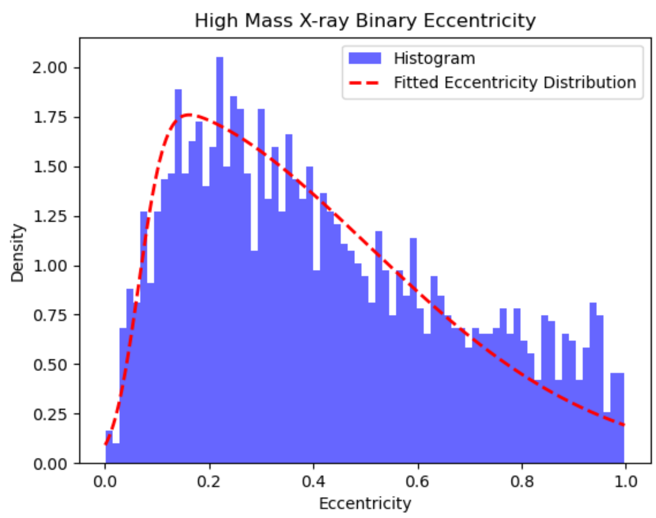
Results

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

3.1 Detached

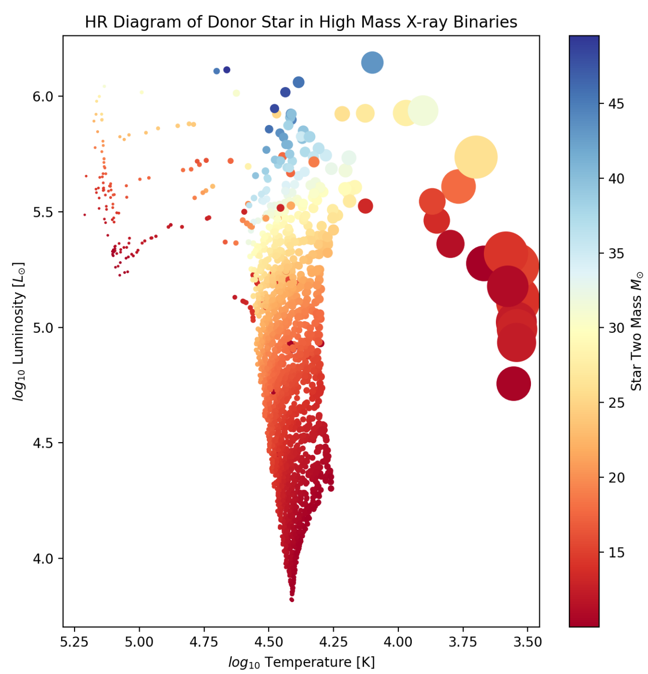
In detached binaries, there is still the possibility for mass transfer. These systems are typically called HMXBs. I found that these systems have a distribution as pictured. Note these systems are only ones with full blown RLO due to simulation of WA constraints





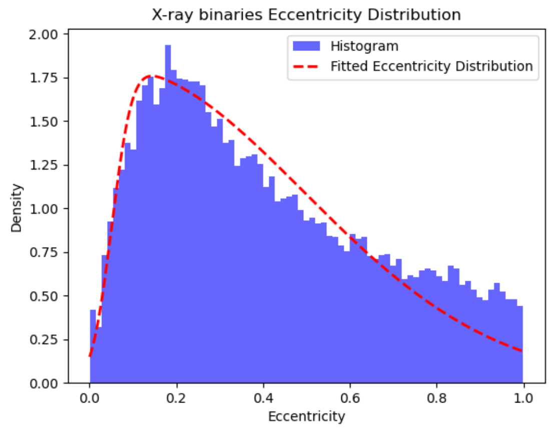
Additionally, HMXBs fall in this region on the HR diagram

Size of dot corresponds to Donor radius

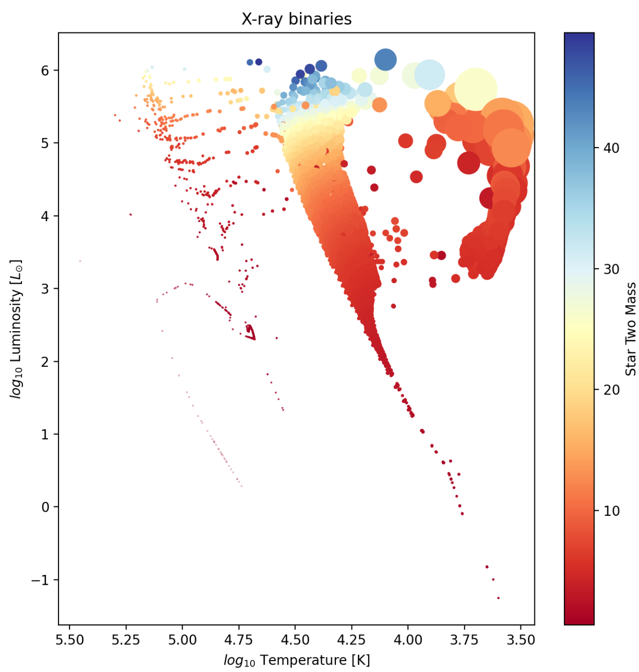


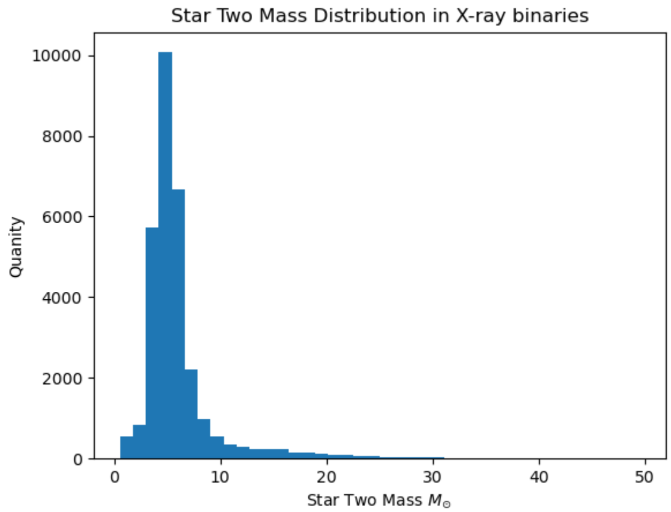
3.2 Roche Lobe Overflow

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



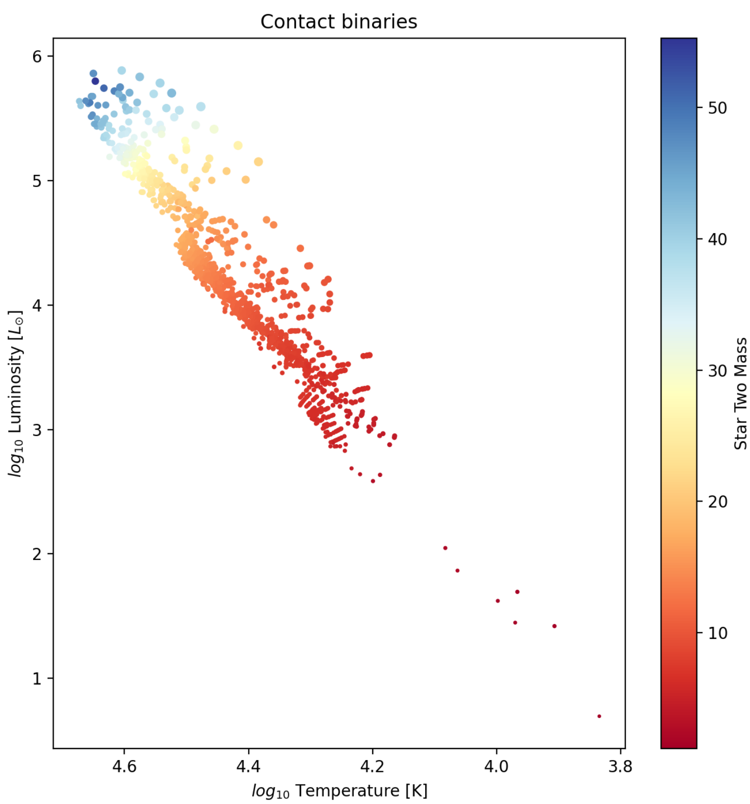


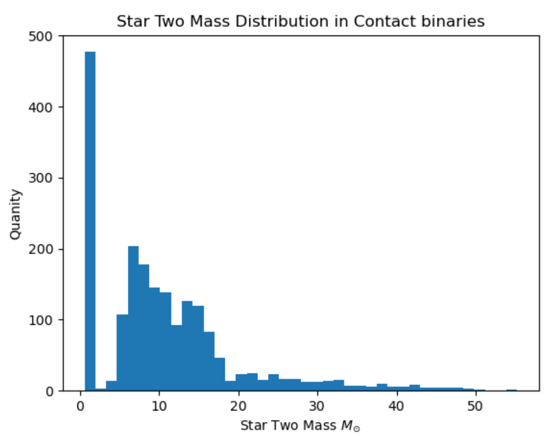
(cite and insert figs)

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 [5] 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.

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