Mass Transfer in Binary Stars Research Essay

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1 Summary

In this paper I investigated the effects of mass transfer in binary star systems. In order to do this, I used data from three observed systems (V404 Cygni, Vela X-1, and W Ursae Majoris) in conjunction with a large (one million simulated stars) private dataset which I obtained from Northwestern CIERA (`https://ciera.northwestern.edu/`). This data was simulated on the NU high performance computing cluster **Quest**.

I first used the Roche Lobe model to categorize the systems into specific stages, allowing me to investigate the systems to a greater depth. To analyze the data I used Python with a multitude of packages (NumPy, Matplotlib, Bokeh, Pandas). 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 quickly generate variable HR diagrams for any and all types of datasets, quickly variables as needed while automatically applying them to all the curated graphs. This script can be found on the GitHub at `https://github.com/PiersonLip/Honors-Independent-Study/blob/main/Code/HRDiagram.py`.

Additionally, I wrote the paper in LaTeX(`https://www.latex-project.org/`), 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.

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 worked well with LaTeX.

2 Research Question

My research question was 'How does mass transfer affect the evolution of binary stars?' This question was prompted by a previous investigation in another population of binary star systems called ultra-compact x-ray binaries. While I was investigating these, they had a unique reaction to mass transfer (a large part of what made them a population). I then became curious how mass transfer affected populations of binaries as a larger whole and decided to further investigate it.

2.0.1 Question Evolution

As I learned more about mass transfer I found that a lot of the states of the Roche Lobe model were temporary, something that the star would evolve into and out of. This did not change the research question itself, but changed the way I was investigating the topic, causing me to look more at the population of stars themselves instead of the current state of the observed systems. I.e. greatly widening the time span I was looking at.

3 Sources

I used **ADS** https://ui.adsabs.harvard.edu/ and **ArXiv** https://arxiv.org/ in order to find recent and up-to-date studies regarding my systems. Additionally, I used the textbook Physics of Binary Star Evolution https://press.princeton.edu/books/hardcover/9780691179070, as it provided the perfect balance of an overview which was also incredibly well cited, allowing me to delve deeper into the topics which I was interested in.

4 Research strategies

After I had the foundational knowledge needed, I started using Python to directly analyze data and apply it to my results. To obtain this foundation I started by using the textbook, which allowed me to get a good grounded understanding, but when I started investigating very specific properties I then began to use academic papers. As I researched I would take my sourced observed data and analyze it both with statistics and graphs. As I analyzed it I would notice various properties or anomalies. When I noticed these, I would first look for an explanation in the textbook, then see if I could find a paper regarding it. This process allowed me to find and correct faults in my process and also discover different properties.

When I began the paper I started working on Overleaf, a tool which serves as a sort of 'Google Docs' for writing LaTeX documents. While at first it worked great, it was severely limiting with its custom figures integration and long compile times. Because of this, I switched to using LaTeX in VS Code, which allowed me to both compile faster, but also quickly use custom figures. Furthermore, storing the entire project locally meant that I could have the code and the paper in the same location while additionally syncing it to GitHub remotely. This allowed me to work on the paper (including all data, code, and figures), from any laptop or desktop.

I worked on all the code in using Python notebook files, as they allowed me to rapidly and seamlessly work on different sections and scripts.

5   Information Evaluation

I evaluated my information through a multitude of ways. The first thing I always looked at was the publishing date. There were plenty of papers which would provide a great foundations of info on a binary system (for example `doi.org/10.1093/mnras/271.1.L10`, which I used for V404 Cygni), but due to their age the actual measurements themselves were out of date. In order to make sure the data I was using was as up-to-date as possible, I would use these papers to lay a groundwork, and then reinforce it with a newer paper with more accurate measurements (for example, `https://doi.org/10.1051/0004-6361/202346571` which had the measurements I used for V404 Cygni). This workflow allowed me to make sure that my information was accurate and also was through enough to catch any mistakes.

I only used expert sources in order to make sure my data and explanations were as accurate as possible.

Throughout my research I would find certain things that would disagree with what some of my other sources stated. Whenever this would happen, I would first try and see if there was an error on my end, whether that be through misunderstanding or a typo in my code, and then I would see if there were other papers on the same topic. This allowed me to correct a lot on my errors, and in the case of V404 Cygni, make sure I was using accurate and up-to-date papers.

6   Information Gathering and Methodology

I used data generated by the script POSYDON 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 these types of binary

stars exist, there is not enough of them to get a true grasp of whole population. Hence, I used POSYDON. This dataset was simulated on the NU High Performance 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 then utilities MESA on a much greater scale in order to simulate full populations of binary stars. The data was stored in the form of a .h5 file, containing a total of $\approx$ 6.1 million rows and 83 columns.

This data was provided in a totally "raw" format containing the entire database. This combined with the sheer size allowed me to tailor it to my needs and various investigations.
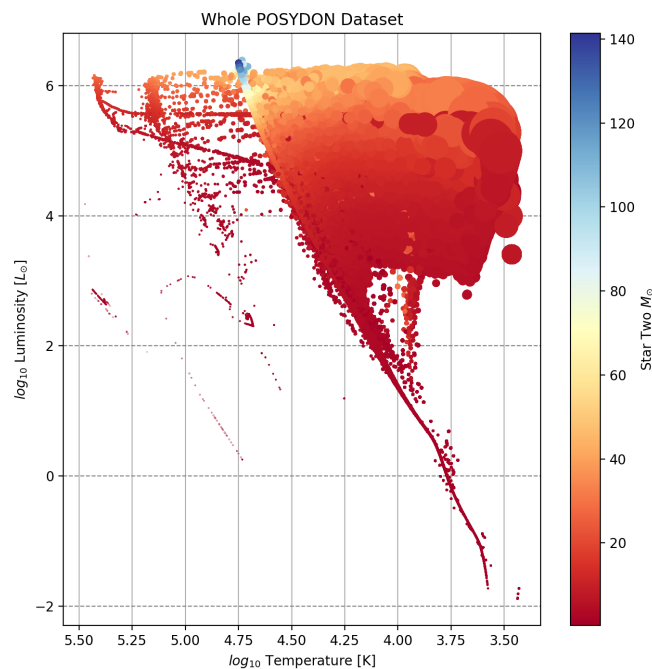

Figure 1: *HR Diagram of the donor star for the full ($\approx$6.1 million points) POSYDON dataset. Note that the color of the plotted points correspond to the solar mass of the donor star. Additionally, the size of each plotted point is logarithmically related to the radius of the plotted star which it represents. This means that for each plotted point, one can evaluate four different variables, something which is rare in 2D graphs. I generated this figure utilizing Matplotlib.*

Binary ID	System State	Orbital Period (days)	$\log_{10}$ Mass Transfer Rate	Donor State	. . .	Donor Mass ($M_\odot$)	Accretor State	Accretor Mass ($M_\odot$)
0	Detached	0.047520	−99.00000	NS			1.196033	Stripped He Core He burning	≈ 1.002
		. . .						. . .	
999, 999	Detached	0.0429883	≈ −80.8	NS			1.196033	Stripped He Core He burning	≈ 0.9957

Table 1: *Example of POSYDON data, heavily modified for readability.*

7 Results

Highly recommend looking at this after fully reading the paper, otherwise this will not make a lot of sense

I learned a massive amount about the processes of mass transfer in binary stars and feel as if I could fluently speak about the topic as a whole. I learned a lot about the physics and math involved in the process and how crucial of a part it plays in the evolution of binary systems. Additionally, I furthered my data analytic skills in Python, learning how to greatly streamline the process. Furthermore, I learned how to use LaTeX for academic writing and how to streamline a workflow consisting of Python, Git, GitHub, and LaTeX.

7.1 RLO

I found a lot of the key factors in mass transfer and how it affected various types of binary stars, with Full-blown RLO being the most key factor in mass transfer in LMXBs, leading to large amounts of x-ray emission. This process had drastic effects on both the donor and accretor star.

7.2 Detached

I found that a large amount of detached systems have mass transfer in some form. Additionally, I found that V404 Cyngi properties did not fall onto a known location on an HR Diagram, something which is incredibly unusual.

7.3 Contact

I found that simulated models have a discrepancy with observed data, something I corroborated with findings from recent papers. I found there was a linear relationship between $\log_{10}$ temperature and $\log_{10}$ luminosity in populations of contact binaries.

8 What Would I change

If I could redo this I would do it all in the workflow I learned in the process. As I learned LaTeX I discovered more and more tools and packages that were suited for my exact needs (section referencing, graph and table labeling, etc.). This meant that as I got further into the paper everything become more streamlined and tidy, but left some of the initial parts crude. If redid this paper I would be able to standardize all of that from the onset, saving me a large amount of time.

Additionally, I wanted to fully simulate my own grid for one of the stars, however, due to time constraints I was unable to.