July 25, 2024

Dear Doctoral Thesis Committee,

Below is my report for the doctoral thesis of Camille Landri in the Faculty of Mathematics and Physics at Charles University. I judge the thesis to be excellent, with only minor/typographical corrections needed, and am recommending a pass with distinction/honours should your institute permit such categories. I provide detailed examples below of the new results presented in each chapter, their relevance to and implications for the field, as well comments on the overall presentation of the thesis and the author's potential for carrying out creative research in the future.

Title: Theory and observations of two stars undergoing strong interaction

Chapter 1 gives a comprehensive introduction to the essential theoretical, computational and observational background needed for studying close binaries. The descriptions and discussions of the physical processes such as tidal circularization and synchronization, as well as mass transfer via Roche lobe overflow and it's stability are well done. Although examples are given for the sun later in Sec. 1.4, the definitions of the various timescales (dynamical, thermal, nuclear) that are used in discussing the details of mass transfer could be included earlier on (i.e., when they are first used or provide a useful reference for readers for this, as well as many of the topics covered, e.g., https://www.astro.ru.nl/~onnop/education/binaries_utrecht_notes/Binaries_ch6-8.pdf). An overview of the complexities of common envelope evolution is also given that nicely highlights again the physics of the different phases, uncertainties and potential outcomes, but also summarizes the present status of the field. In going from the response of the accretor to accretion disks and transients/CVs, the author logically and clearly connects and covers the various topics of the thesis. The result is an introductory chapter that situates the thesis work well, and skillfully ties together the chapters into a coherent body of work.

Finally, the numerical techniques used to study the interactions are described thoroughly, with good explanations of both particle-based and grid-based approaches to the hydrodynamics. Again section 1.4.4. provides a good overview of additional physics that is implemented in the models (gravity) and that could potentially be included in future (e.g., radiative transfer and MHD). A description of the background and techniques relevant for the observational work (time-series, data reduction, line fits, photometry and spectroscopy) could also be useful here or perhaps in an appendix. However, I recognize that the chapter is already quite extensive and that the observations are a smaller focus in the thesis.

Overall, the introduction is a good summary of the relevant background needed, as well as the current status of work in the field. While none of these aspects represents new work by the author, seeing them set out clearly further highlights that the author has good knowledge and familiarity with the underlying details. Indeed the introduction is impressive in its depth and breadth, clarity and utility (would make a nice handout for students starting out), and it also demonstrates the author's ability to see the broader context of their research (the 'big picture').

Chapter 2 presents new observational data of the source OGLE-BLG504.12.201843 accompanied by new analysis. Using published OGLE data as well as DASCH photometry, combined with new I-band observations from 2016-2021, the author presents analysis of 6 outbursts of the system over 18 years of observation. The orbital period of ~0.52 days that was found in Mroz et al 2015 is confirmed and they find similar results for the outburst interval, amplitude, shape and periodicity, noting stronger evidence for ellipsoidal variability. Although not addressed directly, no evidence is given to support the speculation by Mroz et al 2015 that there may be a third body on a wider orbit. Using careful time series analysis of the light curve shape and amplitude during quiescence and outburst, the author finds that a thermally unstable accretion disk, similar to that found in dwarf novae, can account for many of the observed photometric features of the system. The analysis also led to the discovery of small, 0.2 mag flares during quiescence that had not been noted before. Given their amplitude, duration and recurrence interval, the author suggests that they may result from failed smaller outbursts. The first spectroscopic data of the system from the Magellan and SOAR telescopes is also presented. This new data adds further complexities to the system with the absence of emission lines in quiescence and Balmer absorption in outburst (features expected for a system with a white dwarf and outbursts from an accretion disk) and the author suggests that it may be due to a large, weakly irradiated (cold) disk. The analysis of the shapes of the lines during outburst and the orbital variability suggests that we may be viewing the system at low inclination. Finally a detailed comparison of the system to other known dwarf novae is given, describing how the observed and inferred properties, e.g., mass-transfer rates, outburst duration, cycle length, amplitude, orbital period, and position on the HR diagram can be used to further constrain the nature of the component stars and the underlying cause of the outbursts. The conclusion is that OGLE-BLG504.12.201843 may be an extreme dwarf nova system.

The chapter nicely demonstrates that OGLE-BLG504.12.201843 is an important system as it raises new questions about the nature of dwarf novae. In particular, the origin of the small flares is still unknown and although it's properties are extreme, the fact that the light curves show the brightening before an outburst, as predicted by the disk instability model, raises questions about the link to, and processes that may suppress this in other systems. The author's skill in using observational data reduction tools and techniques (IRAF, fitting spectral lines with Gaussian profiles, time-series analysis) and strong theoretical grounding (e.g., in disk physics, ellipsoidal variations, mass transfer) has resulted in work that advances our understanding of the system and the field more broadly. The need for further multi-wavelength (optical and UV), higher resolution and signal to noise ratio observations proposed by the author will help push this further.

Chapter 3 presents a model of the close interaction in a massive binary system consisting of a 20 Msun red supergiant (RSG) with a 2 Msun companion on such a highly eccentric orbit that it grazes the outer RSG's envelope at periastron. These are the first detailed 3D hydrodynamic simulations of such an interaction. The numerical set-up is clearly described, including the publicly available SPH code, PHANTOM, and the schemes that the author has incorporated to capture physical processes such as a realistic structure for the outer RSG atmosphere (derived from 1D MESA models), the point mass companion, radiative cooling and radiation pressure on dust. The author notes the limitations of these approximations, however, given the large uncertainties (e.g., the composition of O-rich condensates and grains, the dominant wind-driving mechanism in RSGs etc), they are more than adequate for this proof-of-concept model, and on par or better than the majority of typical cool giant+companion 3D models. The author studied the outflow and ejecta geometry, orbital evolution and mass-loss properties for ~13 grazing orbits by which time (~200yrs) the orbital separation decreases so that the system undergoes common envelope evolution and the simulation is stopped. They find that a significant amount of mass is lost (~0.19 Msun), ejected and then driven as a wind (by radiation pressure on dust), and they note that this is likely an upper limit given the generous cooling and dust acceleration schemes.

The interaction is studied for different resolutions, with and without cooling and radiation pressure on dust (adiabatic). Cooling and dust driving results in strongly asymmetric outflows as shown in the series of snapshot cross-sections. It would be interesting to check the resolution (smoothing lengths, h) for the material in the outermost regions, e.g., for Fig. 3.8 (this can be done by making a rendered plot of the smoothing length or by pressing "c" at a point in *splash* (this draws a circle of radius h for that point). If h is larger than the structures observed, it may be better to not include those regions in the plots (this is not unexpected, edge effects in SPH make the properties of the outermost particles inaccurate - basically with vacuum background initialisations, particles at the edge have to have extra large h's in order to get the correct number of neighbours).

The new results are nicely put in context and compared to observations of the RSG binary population and connected to the enigmatic RSG, VY CMA (the inspiration for the author's study). The detailed discussion of the observed rates of RSG binarity (~30% of massive stars), as well as the origin and fate of these systems (e.g., X-ray binaries, the elusive Thorne-Zytkow Objects and Type IIn supernovae), demonstrates the broad applications of this work for evolutionary pathways that involve RSG+companion interactions. The author has put forward a creative and plausible mechanism to explain the formation of the highly structured circumstellar medium around VY CMA, matching the majority of its characteristics (mass, velocity and mass-loss timescale). The models provide excellent motivation for future simulations and higher resolution and sensitivity submm/mm observations (e.g., with the coming ALMA upgrade).

The implications for core-collapse supernovae are also important. With earlier and higher resolution observations, an increasing number are found to have evidence for strong ejecta-circumstellar medium interaction (e.g., Type IIn supernovae). The author demonstrates that the amount of material ejected, the close proximity to the source (80% of mass lost within ~100AU) and wind terminal velocities (~60 km/s) are in line with observational estimates. The section on the relevance for the Thorne-Zytkow Objects is missing and should be fixed, however, it was available in the online version of the paper. The work presented is also interesting given that it will result in changes in the RSG envelope structure and properties, setting the stage for and impacting the subsequent common envelope evolution (as demonstrated in Chapter 4).

Overall, the author has done an excellent job in creating an efficient model of, and characterizing in 3D, the RSG+grazing companion scenario, demonstrates excellent understanding of the limitations of the model, clearly outlines possible avenues for improving it, and describes what promises to be impactful future work.

Chapter 4 presents the first 3D hydrodynamics study of the impact of a rejuvenated donor star on the evolution and mass-loss properties of a binary system undergoing common envelope interaction. The initial conditions are described for two different 1D MESA models from Renzo et al. 2023 - one in which the donor is a massive (~18 Msun), single, non-rotating star, and the other in which the donor has accreted material (increasing its mass to ~18 Msun) during a previous phase of Case B mass transfer. Since stellar evolution codes have different prescriptions for spin-up due to accretion, it would be good to include an explicit description of the rotational properties of the rejuvenated donor (p86). In going from 1D to 3D in FLASH, the inner regions of these models are replaced by polytropic gas and a particle for the donor core. It would be useful to have a schematic diagram to show the Rcore regions and the regions replaced by a particle, or these different regions could be indicated on e.g., Fig. 4.1. After the donor stars are relaxed on the grid (embedded in "fluff"), they interact with a 1.4 Msun companion that is also represented by a gravitational particle.

The author demonstrates that the rejuvenated donor, with the associated changes to the structure of the core-envelope boundary region (the density, composition and lower binding energy) results in a much faster slow grazing orbit (2 years vs 6 years for the non-rejuvenated donor), and a relatively similar speed for the fast inspiral phase. Thus the timescale for the inspiral phase with a rejuvenated donor (at least the time to reach minimum separation of the cores) is half (4.5 years) that compared to the non-rejuvenated donor case. The author puts forward a good explanation for this, the increased mass in surface layers built up during accretion resulting in stronger drag, and the limited core resolution unable to fully capture the impact of the lower binding energy). Also due to the limited resolution, the outcome (merge or stabilize to form a tight binary) for both the rejuvenated and non-rejuvenated cases is uncertain. As noted by the author, although it appears that the cores merge, better resolving the inner regions could result in following the interaction for longer and the transfer of sufficient energy to unbind the envelope. Similar uncertainties result for the related mass lost; improving the resolution and energy treatment may reduce the discrepancy with the different bound-unbound energy criteria (including internal energy or not).

The snapshot cross-sections and meridional profiles presented nicely demonstrate the extent to which the outflow morphology is also impacted, with tighter spiral structures ejected, and denser material in the equatorial regions (polar angles ~ -50 to 50 degrees) compared to the poles for the rejuvenated case, both for the inner and outer regions. The slower inspiral process for the non-rejuvenated donor allows the gas to expand further resulting in a more spherically symmetric ejecta. The asymmetries in the rejuvenated case have important implications for a wide range of topics, e.g., the formation of dust structures in the circumstellar medium, and may be a good observational signature for these types of interactions (though it should be noted that this will be somewhat degenerate with companion mass - more massive companions will lead to stronger equatorial focusing of the ejecta). The author also describes in detail the strong implications for the formation of double neutron star and black hole binaries, luminous red novae, Thorne-Zytkow Objects in the case of a neutron star companion, and supernova explosions (the supernova ejecta-dense circumstellar medium interaction for producing Type IIn or ultra-luminous supernovae). They highlight that these results imply that there may be a complex interplay with other processes such as the injection of energy into or ablation of the donor's envelope when its companion explodes as a supernova, together with subsequent mass transfer phases that may strip the donor's dense, outer layers.

Overall, the author has introduced an additional ingredient to the common envelope problem, and demonstrated the importance of properly capturing the evolutionary history of the stars prior to the interaction.

Conclusion presents an excellent summary of the work, its implications and future avenues to pursue. The new results presented in Chapters 2-4 fundamentally impact and are critical for our understanding of the formation and evolution of a wide range of systems, from mergers, to cataclysmic variables and transients. The work is also timely given the immense current and future growth in gravitational wave and time-domain astronomy.

Aside from a few minor corrections/typos (see attached), the writing and structure of the thesis is logical, clear and very well done. The author has done an excellent job with the figures, creating interesting schematics and the data plots are clear, necessary and compelling. The tables are also useful for quick referencing and are relevant. The references are appropriate and represent good coverage and familiarity with the relevant literature in the field. Repetitions in the 'References' section (likely due to citation of the same paper in different chapters) should be removed and journal names should be consistent (either in full or abbreviated).

Through this thesis the author has demonstrated deep and wide-ranging skills with observational data and analysis and numerical modelling with both a grid-based and particle-based code. They are extremely well positioned to push our understanding of close binary interactions and stellar evolution more broadly. With sufficient access to computational resources, the parameter space can be expanded even further to systems with different compositions, metallicities, rotation rates, mass ratios and orbital parameters. The impressive use of different numerical techniques means that detailed studies of the impact of the tools themselves could also be carried out, e.g., resolution and convergence studies, as well as comparisons between the results from FLASH and Phantom for the same problem.

Overall, the work in this thesis not only meets the requirements for a Ph.D., but is also sufficiently creative, forefront and thorough that I am marking it as excellent, and if available, should be considered for distinction/honours. I congratulate the author on a fine piece of work, and look forward to hearing about upcoming results.