SYRACUSE UNIVERSITY
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Physics

Dear thesis committee members, August 3, 2025

I have read the thesis by Jakub Cehula, ``Theory of stellar mass loss: from binary stars to magnetars," in its entirety. It is clear from this work -- and the fact that the PhD candidate has published three works on the main three chapters -- that Jakub is capable of performing high-quality, novel, and independent research. I will provide an overview and my comments of each chapter below, but overall I strongly recommend that the candidate be awarded his PhD in Theoretical Physics, Astronomy and Astrophysics.

The Introduction (Chapter 1) provides an excellent overview of the properties and types of stellar binary systems, as well as motivation for analyzing the problem of mass transfer in binaries; it also establishes the necessary underpinnings for the physics of binary systems (i.e., the Roche geometry/non-inertial frames), stellar interiors and evolution, magnetars and their flares, the r-process, and special relativistic hydrodynamics. The diversity of the material contained in the introduction, subsequently covered in greater detail in ensuing chapters, highlights the breadth of the thesis and the author's understanding of general astrophysical phenomena and analytical and numerical methods.

Chapter 2 describes a new model for predicting mass transfer rates in close binaries, and specifically develops an analytical prescription where material is funneled through a nozzle at the inner Lagrange point (L1). The model does not assume that the material flows parallel to equipotential surfaces, and analyzes time-independent and one-dimensional fluid equations per flows alongaveraged over the plane perpendicular to the binary semimajor axis. As for other one-dimensional flow problems (e.g., Bondi accretion), the smooth passage of the fluid variables through a sonic point constrains the mass-loss rate of the donor star. The main difference between the model proposed in the thesis and pre-existing models is that the flow is no longer confined to equipotentials, and is instead viewed as more analogous to a stellar wind, but where the flow converges toward a point (as opposed to emanating from a spherical region). The model is generalized to incorporate three different equations of state (EOS): optically thin (i.e., isothermal), optically thick (i.e., adiabatic), and a more general EOS that accounts for differences in, e.g., ionization as a function of distance along the line joining the two objects (or, as described in the thesis, as a function of the potential). The model is then applied to different stars generated with MESA, for which flow rates across the L1 point are derived and compared to existing models. It is demonstrated that the new model makes new predictions for the evolution of certain binary systems when compared to those in the literature.

Chapter 3 considers the importance of radiation on the dynamics of the gas flow in interacting binaries, and it is -- convincingly -- argued that radiation could be quite important for such systems, as the inner Lagrange point L1 represents a location where the gradient in the gravitational potential vanishes. Importantly, this contrasts the spherically symmetric case in which the classic Eddington limit is traditionally derived, where the gravitational force and (optically thick) radiative force both satisfy inverse-square relations. The main focus of the chapter is the scenario in which the donor star (presumed massive and for which radiation pressure is especially important) possesses a super-Eddington surface layer that resides within the L1 point, which more efficiently drives material onto the accretors, though the sub-Eddington case is also considered (Section 3.4). The author derives solutions to the radiation-hydrodynamics equations under various sets of assumptions, including the optically thick and thin limits (i.e., the equation of state relevant to the gas), and discusses other approximations used to reduce the complexity of the equations (i.e., the use

of von Zeipel's theorem). The author then applies the solutions to different donor stars constructed with MESA, both those below the Eddington limit and above, and compares their results for the mass flow rate across the L1 point to previous estimates.

Chapter 4 presents an analysis of the injection of a large amount of energy into the atmosphere of a neutron star, where the energy is presumed to come from the rapid dissipation of magnetic energy associated with reconnection. Specifically, the dissipation of magnetic energy occurs at the expense of the increase in thermal energy, which subsequently generates two shockwaves: one outward-moving at ~ c in the low-density surroundings of the neutron star, and a second that propagates inward into the neutron-star crust that subsequently stalls once the pressure associated with the giant flare, P_{GF}, is comparable to the crust pressure, P_{cr}. There is then a second ejection episode (i.e., in addition to the relativistic and outward-propagating shock) that follows the re-expansion of the shock-heated neutron-star crust, which -- as argued in the chapter -- could give rise to a kilonova-like afterglow owing to this free-neutron-rich secondary ejecta. The chapter presents some analytical approximations to the structure of the NS crust that are used to determine the stall radius of the shock, which is analyzed numerically with a set of hydrodynamical simulations that span a range of flare energies. The results of the simulations corroborate the notion that this physical setup can reproduce some of the observational signatures of magnetar GF's that are difficult to generate with other models, but there are not-insubstantial differences in the outcome of the simulations that arise from the choice of Riemann solver and interpolation scheme.

The supplementary chapter contains material from two papers co-authored by the candidate, in which their model for magnetar GFs is used to constrain the observational signatures of the r-process reactions that result from the ejection of the neutron star crust (following its heating from the propagation of the shockwave into its interior), and simultaneously suggest that a \gamma-ray flare could accompany such reactions. The results demonstrate that the model provides a reasonable fit to the electromagnetic data from the SGR 1806-20 GF, and that this source of r-process enrichment could have significant implications for galactic chemical evolution.

In summary, this thesis presents a compendium of novel results and methodologies, demonstrates that the candidate is capable of independent research (this is especially evident from the fact that the advisor is not a co-author on the paper on which Chapter 4 is based), and contains numerous areas for future study and more detailed understanding of the physical systems considered. I reiterate the statement made at the beginning of this letter: I strongly recommend that the candidate be awarded his PhD in Theoretical Physics, Astronomy and Astrophysics.

Sincerely,

Eric Coughlin, Assistant Professor, Physics Department, Syracuse University