Nonlinear Tidal Dissipation in Binary White Dwarfs

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1 Background and Proposed Research

1.1 White Dwarf Binaries

Compact white dwarf (WD) binary systems, with orbital periods in the range of minutes to hours, are important for a range of astrophysical problems. They are the most important sources of gravitational waves (GWs) for the Laser Interferometric Space Antenna (LISA)[1]. They are also thought to produce interesting optical transients such as tidal novae[2], underluminous supernovae[3], and Ca-rich fast transients[4]. Most importantly, they have been proposed as the likely progenitors of type Ia supernovae (e.g. [5, 6] or more recently[7, 8]). While presently only a few tens of compact WD binaries are known[9], *Gaia* (currently gathering data) is expected to expand the catalog to a few hundred[9] (results based on *Gaia*'s second data release have already begun to appear[10, 11]), and the Large Synoptic Survey Telescope (LSST, first light scheduled for 2020) will likely detect a few thousand more[9]. These observations will significantly advance the understanding of WD binaries. My proposed theoretical and computational research is well-timed to take advantage of these new advances.

In spite of the broad importance of WD binaries, the evolution of these systems prior to their final merger is not well understood. Much of this uncertainty comes from our imprecise understanding of tidal interactions, which play an important role during a compact WD binary's inspiral[12]. Studies show that these interactions manifest as tidal excitation of internal gravity waves (IGW), waves in the WD fluid restored by the buoyancy force due to density stratification[13]. As these waves propagate outwards towards the surface, they grow in amplitude until they break, as do ocean waves on a shore, and transfer both energy and angular momentum from the binary orbit to the outer envelope of the WD[12, 13].

Previous works have found that this tidal dissipation mechanism can generate significantly more energy than thermal radiation from the WD surface alone and is thus a major contributor to the WD energy budget[12, 14]. However, these works parameterized the wave breaking process without hydrodynamical simulations. The details of tidal dissipation, namely the location and spatial extent of the wave breaking, affect the observable outcome: dissipation near the surface of the WD can be efficiently radiated away and simply brightens the WD, while dissipation deep in the WD causes an energy buildup that results in energetic flares[2]. Similar works in other fields find that numerical simulations capturing the strongly nonlinear wave breaking process find new behavior that cannot be described by linear and weakly nonlinear theory[15, 16]. Such fully nonlinear numerical simulations have not been performed for WDs.

1.2 Proposed Research

Characterizing the location and spatial extent of tidal dissipation in WD binaries will require numerical simulation to capture the turbulent cascade to small scales causing wave breaking. **I propose to study the dynamical effects of tidal dissipation via nonlinear IGW breaking in binary WDs.** To accomplish this, I aim to address the following three aims:

- Characterize the location, spatial extent, and other properties of wave breaking in realistic WD models via direct numerical simulation. The location and spatial extent will furnish a simple yet effective parameterization of tidal dissipation. §2 describes the steps required for this aim.
- Predict signatures of tidal dissipation over a wide range of possible WD systems. In particular, I will describe the impact of tidal heating on the apparent temperature of a binary WD and maybe even the production of observable flares. §3 details my plan to do so.
- Compute modified GW templates for LISA that account for changes in the phase evolution of the orbit due to tidal dissipation. §4 elaborates on how I will perform this computation.

2 Nonlinear Tidal Dissipation

2.1 Background and Preliminary Work

The current understanding of tidal synchronization in WD binaries is laid out in [12]: a tidally-excited train of IGW undergoes wave breaking in the outer envelope of the WD, locally depositing angular momentum and synchronizing the WD spin to the binary orbit. A similar process may also operate in stellar binaries consisting of early type stars[17, 18], the only major difference being in the specifics of wave excitation[1]. Nevertheless, direct numerical simulation of the wave breaking process has not been performed in either of these systems. Since wave breaking is a strongly nonlinear phenomenon, where a larger wave breaks down into many smaller-scale waves, numerical simulation is paramount to an accurate understanding of IGW breaking.

IGW breaking has been studied in detail in atmospheric sciences. The wave breaking process proceeds as follows: initially, as the IGW reaches nonlinear amplitudes, it breaks down via the parametric subharmonic instability and transfers energy and angular momentum from the wave to the mean flow of the fluid[19]. Subsequently, after the mean flow velocity reaches the horizontal phase velocity of the IGW, a critical layer through which the IGW cannot propagate forms. A well-known calculation shows that the IGW is nearly completely absorbed at this critical layer in the linear approximation and endows the atmosphere with a mean horizontal flow[20, 21]. However, when this mean flow absorption was numerically studied including full nonlinear interactions, new phenomena not described by the linear theory (reflection off the critical layer and sharpening of the mean flow) were observed[15, 22] that affected the evolution of the atmosphere over time. *This highlights the importance of numerical simulation in capturing the wave breaking process.*

To gain insight into the tidal dissipation process, I began by using the spectral hydrodynamics code Dedalus[23] to study IGW breaking in a 2D isothermal, stratified atmosphere. A spectral code

[1]While IGWs in stars are excited at their radiative-convective boundaries, IGWs in WDs are excited at sharp changes in composition.

like Dedalus is ideal for simulating complex hydrodynamical phenomena, as spectral methods have no inherent numerical viscosity and so better resolve the nonlinear cascade to small length scales in wave breaking.

Working with Dr. Daniel Lecoanet (Princeton; one of the authors of the Dedalus code) and my advisor, Prof. Dong Lai, I simulated an upward-propagating IGW wavetrain excited at the bottom of the atmosphere. I observe the excited wave breaking and depositing horizontal momentum in the fluid, causing the fluid to acquire an average horizontal flow, consistent with previous studies[12]. I derive simple formulae for the location and spatial extent of the dissipation zone where the IGW is absorbed by the fluid. More interestingly, I observe partial reflection of the IGW at the synchronization layer[24], a phenomenon not considered in the current astrophysical literature but consistent with the aforementioned results[15]. A sample simulation is presented in Fig. 1. I am preparing these results for publication[24].

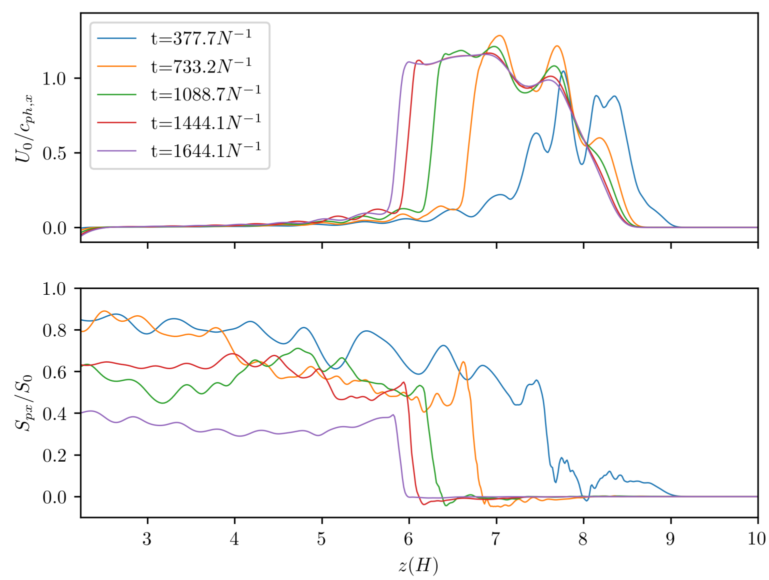

Figure 1: The evolution of the average horizontal flow velocity of the fluid U_0 (in units of $c_{ph,x}$ the horizontal phase velocity of the IGW) and horizontal momentum flux contained in the IGW $S_{px}(z)$ (in units of the total excited flux S_0) for one of my simulations. Different colored lines correspond to different times in the simulation. Times are measured in units of N^{-1}, the inverse of the Brunt-Väisälä frequency (or the buoyancy period), and heights in units of H the scale height of the density stratification. IGW are excited at $z = 2H$ and propagate to higher z before undergoing wave breaking. The sharp decrease in S_{px} is the location of the critical layer where the IGW breaks and drives U_0 towards $c_{ph,x}$; it moves to lower z over time. The apparent decrease in S_{px} at later times indicates reflection off the critical layer.

2.2 Proposed Work

It is therefore clear that full numerical modeling of IGW breaking is necessary to fully characterize tidal dissipation. The first aim of my proposal is then: **I will extend my preliminary results to characterize the dynamics of nonlinear IGW breaking in realistic WDs.** Via numerical simulation, I will develop simple models for tidal dissipation that can be used to study WD evolution under tidal heating without performing further simulations. I will continue my work in the following stages:

- I will perform simulations examining the validity of my results in more realistic geometries, including polar and spherical geometries. I will continue to use Dedalus, which also supports these coordinate systems.
- I will extend my simulations to realistic WD models and equations of state such as those in [25], continuing to track the location and spatial extent of the dissipation layer as well as any new phenomena. As WDs vary widely in composition and effective temperature, studying representative WD models is vital to obtaining a robust characterization of tidal dissipation. My selected WD models are those used in the current literature[12, 14].

3 Tidal Heating Thermodynamics

3.1 Background

As discussed earlier, compact WD binaries exhibit a range of observed and hypothesized optical transients. Tidal novae[2], underluminous supernovae[3], and Ca-rich fast transients[4] are all hypothesized to arise in WD binary systems. Given that tidal heating can become a significant contributor to a WD's total energy budget, a realistic model of tidal dissipation is important to understanding a binary WD's thermodynamic evolution during inspiral.

In [2] (hereafter FL), the authors use MESA to study the production of tidal novae in binary WDs. A simple two-zone parameterization where the tidal heat is deposited throughout the outer zone was used to model tidal dissipation. They find that cool WDs in sufficiently compact binaries (orbital period $\lesssim 15$ minutes) may incur a thermonuclear detonation of the hydrogen envelope. WD binaries with such short orbital periods have been observed, e.g. SDSS J065133+284423 has a period of 12.75 minutes[26]. FL fits the observed properties of SDSS J065133+284423 to their tidal heating models and finds evidence for tidal heating of the secondary WD in SDSS J065133+284423. From their fits, FL are able to estimate the temperature of the WD in the absence of tidal heating. As WDs form around a well known temperature and cool predictably over time, accounting for tidal heating equates to a large correction to the age of the WD. This illustrates the importance of accurately modeling tidal interactions when inferring physical properties.

3.2 Proposed Work

With the tidal dissipation models I will develop, I will be able to perform a simulation similar to that in FL but with a more realistic tidal interaction. The second aim of my proposal is accordingly: **I will use my tidal dissipation profiles to simulate a binary WD undergoing tidal heating and make comparisons to observational data.** The location of the tidal heating is a key ingredient in determining whether deposited energy can be efficiently transfered away or whether the WD experiences sudden detonations. As such, an improved understanding of the properties of tidal dissipation is important to proper forecasting of binary WDs' thermodynamic evolution. Moreover, while only a few sufficiently compact WD binaries were available at the time of writing of FL, *Gaia* data releases 2 and 3 will provide many more compact WD binaries to examine for evidence of tidal heating.

Using MESA, I will evolve various WD models undergoing tidal heating. From these simulations, I will extract the increased temperature of the WDs and make comparisons to observational data, in particular to WDs in new *Gaia* data releases. I will also identify the occurrence rate and observational properties of any predicted optical transients such as tidal novae and attempt to identify them among existing detected events. Predictions of the occurence rates of such phenomena are vital to guiding future observations. Finally, comparison of observational data from known WD binaries to simulations could yield new insights to the behavior of degenerate matter.

4 Tidal Heating and LISA

As discussed earlier, WD binaries are a primary source of GW radiation for LISA. LISA will attain optimal sensitivity at frequencies 10^{-4}–10^{-1} Hz[27]. Exactly in this frequency range, tidal effects act to synchronize the orbit of the WDs to the binary orbit and transfer energy from the orbit into the WDs. While the decay of the binary orbit is still mostly driven by GW radiation, the tidal energy dissipation rate grows to $\sim 10^{-2}$ the GW energy dissipation[12, 14]. An effect of such a magnitude causes the phase of the emitted GWs to significantly from the point-mass binary prediction; the emitted wave may exhibit "missing cycles" due to tidal effects[12]. GW astronomy uses matched filtering, where a library of template waveforms is matched against instrument data, to identify GW signals. As such, the accuracy and completeness of the template library is of utmost importance.

The final aim of my proposal is then: **I will use my tidal dissipation model to compute WD binary GW waveforms including tidal dissipation for use in the LISA detection pipeline**. This aim is much less computationally expensive than it appears: LISA-band WD binaries can be well described using the Newtonian dynamics of two co-orbiting point masses[28]. The resultant GW emission can then be accurately computed using the weak gravity quadrupole approximation (see e.g. [9, 29]). Under these two approximations, the GW waveform can be computed analytically without resorting to numerical relativity simulations at all, an enormous computational savings. Thus, I will compute GW waveforms accounting for the additional phase evolution due to tidal dissipation. I will publish my corrected waveforms for use by LISA and the GW community.

5 Project Timeline

During the first year of work and first half of the second year, I will complete my tidal dissipation model. I anticipate the extension of my 2D plane-parallel work to more complex geometries will be complete within the first half year, while the extension to realistic WD models will take up to a year. I expect that these two results together will produce one peer-reviewed publication in addition to the one currently in preparation.

During the following year, I will use my tidal dissipation model to perform MESA simulations of tidally heated WDs and compare to observational data. I expect my MESA simulations and extracting appropriate observables to take about half a year. I then intend to spend another half year analyzing observational data for potential signatures of tidal heating or tidal novae. I expect both of these phases will produce peer-reviewed publications.

Finally, in the last six months I will compute WD binary GW templates for use by the LISA community. This work will also produce one peer-reviewed publication.

6 Relevance to NASA Objectives

This project is extremely relevant to the NASA Astrophysics research program. My work directly relates to (i) the interactions of particles under the extreme conditions found in astrophysical situations, (ii) how complex systems create and shape the structure and composition of the universe on all scales, and (iii) the development of new techniques that can be applied to future major missions.

My work will improve understanding of possible energetic phenomena that can occur in compact object binaries. My results concerning angular momentum transfer via IGW breaking will be applicable to astrophysical systems beyond WD binaries, for instance angular momentum transfer in stars[30]. I will devise new ways of analyzing astrophysically interesting systems in *Gaia* and LSST. Finally, my GW templates will be important for LISA GW detection efforts.

My work has direct relevance to NASA missions in the detectability of astrophysical transients related to WD binaries. For instance, tidal novae are theorized to have a similar observational signature to dwarf novae which have been observed with Chandra and the Hubble Space Telescope, among others.

References

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