Nonlinear Tidal Dissipation in Binary White Dwarfs

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1 White Dwarf Binaries

Compact white dwarf (WD) binary systems, with orbital periods in the range of minutes to hours, are important for several topics in astrophysics. They are expected to be important sources of gravitational wave (GW) radiation for the Laser Interferometric Space Antenna (LISA)[1]. They are also thought to be likely progenitors of type Ia supernovae (e.g. [2, 3] or more recently[4, 5]). While presently only a few tens of compact WD binaries are known, *Gaia* (currently gathering data) is expected to expand the catalog to a few hundred, and the Large Synoptic Survey Telescope (LSST, first light scheduled for 2020) is expected to detect a few thousand more[6]. These observations are expected to significantly advance understanding of WD binaries: results based on *Gaia*'s second data release have already begun to appear[7, 8]. The proposed research is well-timed to take advantage of these new resources.

In spite of the broad importance of WD binaries, the evolution of these systems pre-merger is sparsely studied. In particular, compact WD binaries are expected to exhibit major tidal interactions. In these interactions, tidal forces from the companion WD excite internal gravity waves (IGW), displacements in the WD fluid experiencing a buoyant restoring force due to density stratification. As these waves propagate outwards from where they are excited, they grow in amplitude until they break, as do ocean waves on a shore, and deposit both energy and angular momentum from the binary orbit in the outer envelope of the WD.

Previous works have shown 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[9, 10]. However, these works treated the nonlinear wave breaking in a parameterized fashion. Related works in other fields find that properly including nonlinear phenomena in hydrodynamical wave breaking produces drastically different IGW dissipation behavior[11, 12]. Such fully nonlinear studies have not been performed for WD binaries but are important for the thermal and orbital evolution of WDs undergoing tidal heating. Characterizing this nonlinear tidal dissipation will require numerical simulation to capture the turbulent cascade to small scales that drives IGW dissipation.

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 that can substitute full hydrodynamic simulation.

- 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.

- Compute modified GW templates for LISA that account for changes in the phase evolution of the orbit due to tidal dissipation.

2 Nonlinear Tidal Dissipation

2.1 Background and Preliminary Work

The current understanding of tidal synchronization in WD binaries is laid out in [9]: 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 orbit. Such a process is broadly consistent with canonical models of tidal synchronization in stars[13, 14], the only major difference being in the specifics of wave excitation[1]. While this tidal synchronization mechanism is generally accepted, direct numerical simulation of the wave breaking process is sparse. 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 is well studied in atmospheric sciences. The wave breaking process proceeds as follows: initially, the universal instability of an IGW to the parametric subharmonic instability is responsible for transfering energy and angular momentum from the unstable wave to the mean flow of the fluid[15]. Subsequently, after the mean flow velocity reaches the horizontal phase velocity of the IGW, a well-known calculation shows that the IGW is nearly completely absorbed by the mean flow in the linear approximation and endowing the atmosphere with a mean horizontal flow[16, 17]. However, when this mean flow absorption was numerically studied including full nonlinear interactions, *new phenomena not described by the linear theory were observed*[11, 18]. This highlights the importance of numerical simulation in capturing the wave breaking process.

To this end, I have adapted the spectral hydrodynamic code Dedalus[19] to simulate a plane-parallel IGW wavetrain excited at the bottom of a 2D incompressible fluid. A spectral code like Dedalus is ideal for simulating complex hydrodynamical phenomena as spectral methods have no inherent numerical viscosity and so are more suitable for resolving the nonlinear cascade to small length scales in wave breaking.

In my simulations, I observe IGW propagating upwards from where they are excited, then breaking and depositing horizontal momentum in the fluid, causing the fluid to acquire average horizontal momentum, consistent with literature[9]. 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[20], a phenomenon not considered in the current astrophysical literature but consistent with atmospheric science results[11]. A sample simulation is presented in Fig. 1. I am preparing these results for publication[20].

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

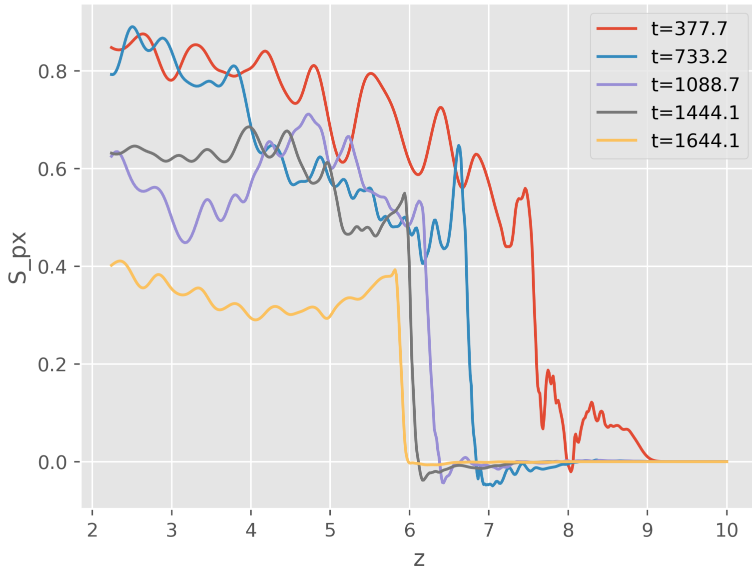

Figure 1: The evolution of the horizontal momentum flux $S_{px}(z)$ over time in a representative simulation. Note that the location where horizontal momentum is deposited by wave breaking, the sharp decrease in S_{px}, moves to lower z at later times; this reflects spinup of the fluid from the top down. The incident flux appears to decrease over time as well, but this is attributed to partial reflection of the IGW off the critical layer. The vertical axis is in units of the total excited horizontal momentum flux, while distances and time are in units of the stratification scale height and the buoyancy period.

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 [21], 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[9, 10].
- With these simulations, I will build a model of tidal dissipation valid for a broad range of WDs. I will package my model as a module for the 1D stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA)[22]. MESA is a popular choice for stellar evolution simulation due to its computational speed and extensibility. It has been used in previous studies to study the evolution of WDs under tidal heating[10, 23]. My module will

provide a parameterized and numerically-validated model of tidal dissipation that can be used to quickly and easily model tidal interactions in binary WDs.

3 Tidal Heating Thermodynamics

3.1 Background

As discussed earlier, compact WD binaries exhibit a range of observed and hypothesized optical transients. Tidal novae[23], underluminous supernovae[24], and Ca-rich fast transients[25] 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 [23] (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[9, 10]. 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[9]. 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. [6, 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 and one MESA module.

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.

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