Nonlinear Tidal Dissipation in Binary White Dwarfs

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1 White Dwarf Binaries

White dwarfs (WDs) are remnants of stellar evolution for stars with mass $\lesssim 8M_{\odot}$. They are some of the densest objects in the universe, fitting a solar mass into an Earth-sized sphere. They are supported against gravity by degeneracy pressure, a quantum mechanical effect arising from subjecting matter to immense pressure. As such, WDs are a unique window into matter under extreme conditions.

WDs are commonly found in binary systems in which two objects orbit their center of mass under mutual gravitational attraction. The companion object ranges from another WD to a supermassive black hole, and all of these binary systems are very important to astrophysics. In particular, merging WD-WD binaries are thought to generate Type Ia supernovae (SNe Ia). Because SNe Ia are highly luminous and can be seen at large distances, they have been used as "standard candles" to probe the expansion rate of the universe (e.g. in 1998 SNe Ia observations provided the first evidence for dark energy[1]). WD binaries also produce gravitational waves (GW), periodic warping of space-time predicted by Einstein's theory of general relativity. The first detection of GWs by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in 2015 heralded a new era of GW astrophysics. Although LIGO cannot detect the low-frequency GWs expected from WD binaries, the space-based Laser Interferometer Space Antenna (LISA) will detect such GWs in the coming decades[2]. As GW astronomy relies on accurate predictions of the expected gravitational waveforms, it is important to build highly precise models of the WD binary inspiral before LISA observation runs begin (scheduled for ~ 2030).

1.1 Tidal Dissipation and Internal Gravity Waves

Tidal dissipation in binary WDs can affect the pre-merger state of the WD and have a major impact on the gravitational waves produced by the binary. Such dissipation arises from the excitation of internal gravity waves (IGWs) in the deep envelope of the WD by the gravitational force of its companion and their subsequent dissipation in the outer envelope[3]. IGWs, not to be confused with the gravitational waves above, are internal displacements in the WD fluid that oscillate and propagate due to a restoring buoyancy force. These waves are analogous to ocean tides on Earth raised by the Moon and the Sun, except that, since WDs do not have sharp surfaces, these waves are internal to the WD. 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 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[3, 4]. However, these works treated nonlinear wave dissipation by a simple parameterization. Related works in other fields find that properly including nonlinear effects produces drastically different IGW dissipation behavior[5]. Such fully nonlinear studies have not been performed for astrophysical binary systems but are important for the thermal and orbital evolution of WD binaries undergoing tidal heating. Characterizing this nonlinear tidal dissipation will require extensive numerical simulation to capture the turbulent cascade to small scales that drives IGW dissipation. This is the goal of my proposed research.

2 Proposed Research

I propose to study the dynamical effects of tidal dissipation via nonlinear IGW breaking in binary WDs using both analytical techniques and numerical simulations. As WDs vary widely in composition and effective temperature, I will study select WD models to capture a wide range of possible phenomena. My research will proceed in the following stages:

I will perform simulations of nonlinear IGW breaking for various WD models. In the last year, I have adapted the spectral hydrodynamic code Dedalus[6] to simulate the simplest WD models. I have excited IGWs in the deep envelope and observed nonlinear dissipation as the wave propagates into the outer envelope. I am in the process of characterizing this dissipation and extending my simulation to other, more realistic WD models. From these simulations, I will compute energy and angular momentum dissipation as a function of time and depth in the envelope for each WD model.

I will apply my dissipation profiles to study tidally heated WDs. Modules for Experiments in Stellar Astrophysics (MESA) is a proven stellar evolution code that is readily extensible to include tidal heating[7]. Packaging my dissipation profiles for each WD model as a MESA module would enable simulations of the binary WDsâĂŹ internal structures evolving under tidal heating. From these simulations, I will extract the WD luminosity over time.

I will compare the simulated binary WD luminosity to observational data to constrain WD properties. For instance, the WD binary SDSS JJ065133+284423 (period 13 minutes) may undergo strong tidal heating and exhibit energetic behavior such as tidal novae[8, 9]. The Large Synoptic Survey Telescope (LSST, expected 2021) is expected to detect a few thousand more WD binaries[10]. I will forecast properties of these samples due to tidal heating.

Tidal dissipation can also affect the orbital evolution of the WD binary and hence its GW emission during inspiral. I will calculate the signature of tidal dissipation on these GWs for each WD model. I will publish my corrected GW waveforms for use by LISA and the GW community.

Intellectual Merit: As discussed, WD binaries are important for being potential progenitors of

Type Ia supernovae, for being future LISA GW sources and for producing various transients that would be detectable. My work will characterize a key ingredient of WD binary evolution that may explain observed properties of such binaries. Additionally, the nonlinear IGW dissipation model I will build has applications beyond WDs binaries. Within astrophysics, IGWs are a key angular momentum transport mechanism in stellar interiors: they are believed to fill a crucial gap in stellar evolution theory[11]. Beyond astrophysics, IGWs are also studied in terrestrial sciences such as oceanography and atmospheric sciences. A robust understanding of nonlinear IGW dissipation would thus have consequences for problems ranging from planetary and stellar evolution to weather patterns and biosphere dynamics on Earth.

Broader Impacts: With the support of the NSF GRFP, I will grow as an effective researcher. I will present my results at conferences and to collaborators in the US and abroad. I will generate videos for use in future Cornell outreach efforts. As hydrodynamical simulation produces visually spectacular videos, my research will be an effective tool in inspiring the public.

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