Nonlinear Tidal Dissipation in White Dwarfs

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1 Introduction: White Dwarf Binaries

White dwarfs (WDs) are remnants of stellar evolution for stars with mass $\lesssim 8M_{sun}$. 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 electron degeneracy pressure, a quantum mechanical effect arising from subjecting electrons to immense pressures Furthermore, they exhibit various chemical compositions, each of which is subject to different physics, and are found in a variety of interesting systems. As such, WDs are a unique and diverse window into matter under extreme conditions.

WDs are commonly found in binaries in which two objects orbit their center of mass under mutual gravitational attraction. The companion object ranges from another WD to a supermassive BH (SMBH), hypothesized to be at the center of galaxies and have mass $\gtrsim 10^5$ solar masses. All of these binary systems are very important to astrophysics. WD-WD binaries are most important for being thought to generate *Type Ia supernovae* in which two WDs merge and initiate runaway thermonuclear fusion that powers an explosion, releasing immense amounts of energy. Because Type Ia supernovae (SNe Ia) are highly luminous, can be seen at large distances and are very consistent, they have been used as a "standard candle" to probe the expansion rate of the universe (e.g. observations of SNe Ia provided the first evidence of the existence of dark energy in the universe).

WD-BH systems are also interesting subjects of study. Recent works indicate that as WDs plunge close to BHs, they will produce observable flares induced by gravitational tidal forces[3]. A WD orbiting a SMBH would also produce gravitational waves, waves of space-time warping as predicted by Einstein's theory of general relativity, that are expected to be detected by the space-based *Laser Interferometer Space Antenna (LISA)* when deployed[5]. Gravitational wave astronomy is an increasingly exciting field as the *Laser Interferometer Gravitational-Wave Observatory (LIGO)* continues to make progress since its first detection in late 2015. As gravitational wave astronomy relies on accurate predictions of the expected signals, it is important to build as accurate models as possible before observation runs begin.

1.1 Tidal Dissipation

The excitation of *internal gravity waves* in the WD by the tidal forces of the companion is an effect exhibited in all of the aforementioned systems. Internal gravity waves, 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 tidally excited gravity waves are analogous to 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 outward from where they are excited, they are expected to grow in amplitude until they break, as do ocean waves on a shore, and deposit both energy and angular momentum in the WD envelope.

Previous work predicts that this dissipation mechanism can generate significantly more energy than thermal radiation from the WD surface alone and are thus a significant contribution to the WD energy budget[1]. The exact radial dissipation profile is of interest since it both is sensitive to WD properties and can produce vastly different observable outcomes. One proposed outcome is a *tidal nova*, in which heating in the WD's degenerate hydrogen layer is sufficient to trigger runaway nuclear fusion and an observable surface explosion[2]. Understanding whether such phenomena occur requires understanding how energy is distributed internally inside a WD.

Internal gravity wave breaking is a nonlinear hydrodynamic phenomenon. Such phenomena are known to require numerical simulation to study. It is therefore paramount to begin numerical study to build dissipation models inside WDs to characterize what phenomena can be observed in different WD models.

2 Proposed Research

We propose to study tidal dissipation via nonlinear gravity wave breaking in white dwarfs using numerical simulation.

Our research will initially consist of numerically computing for various WD models and compositions the energy and angular momentum dissipation profiles inside WDs. Once such profiles are obtained, we intend to add these profiles to existing stellar evolution codes to study the dynamical effects of tidal dissipation. We will attempt to find a compact or even analytical representation of our numerical work to greatly simplify and accelerate such integration. Finally, we will make observational predictions with our results and compare our predictions with existing observed WDs in binaries. Any software and results would be made in accordance with best practice and publicly available for the scientific community.

2.1 Numerical Approach

Much of our proposed research will rely on numerical solutions to fluid dynamical equations. Guided by current literature, we have begun with the Dedalus numerical solver, a modern spectral solver that integrates the fluid equations both quickly and to high accuracy[4]. Dedalus has been shown in current literature to describe turbulence and fluid instabilities well, and our preliminary work supports this conclusion.

For our problem, we will first adapt Dedalus to study gravity waves in the stratified atmosphere/envelope of WDs and later consider global (spherical) WD models. Should Dedalus prove inadequate, we are able (§2.2) and willing to contribute a new hydrodynamic code to the community. Notably, no GPU-accelerated spectral hydrodynamic code has yet been released, which would be of great value to researchers. Nevertheless, in the interest of the proposed science objectives codes will be developed on an as-needed basis.

After characterizing tidal dissipation, we intend to apply our models to WD evolution under tidal heating. Modules for Experiments in Stellar Astrophysics (MESA) is a proven stellar evolution code that would require comparatively little adaptation to incorporate tidal heating in studying WD evolution[6]. A released extension to MESA containing our work would be the most effective way to release our work to prospective users.

2.2 Qualifications

The proposing researcher (YS) and his adviser (DL) are uniquely qualified to pursue such studies. YS has completed a double Bachelors degree in physics and computer science from the California Institute of Technology. He also has ample research experience in numerical simulation and is continuing to pursue academic study in hydrodynamics, turbulence and computation. Finally, he has worked in the software industry for a year and continues to follow discussions of best practice far ahead of those in academia and apply them to his own work.

DL is a co-author of a number of recent papers on WD binaries and is an expert on many related subjects such as fluid dynamics in extreme matter and studies of other compact object systems. Cornell University also houses Saul Teukolsky's research group, one of the pre-eminent numerical relativity groups in the world, which will be frequently consulted for numerical best practices.

2.3 Applications, Interest to the DoD

Although our proposed research deals with astronomical objects and phenomena (WDs and BHs), the tools we use and develop in our research have applications in many areas of physical sciences and engineering. As discussed above, through our research we will develop extensive expertise in nonlinear hydrodynamics (internal gravity waves), radiation physics (radiative transfer and diffusion of heat inside WD), nuclear physics (tidal heating leading to runaway fusion) and numerical computation. Such a research project thus contributes to many science and engineering fields and equips me to tackle an exceptionally large variety of problems.

The proposed research is extremely relevant to Department of Defense (DoD) fields of interest. WDs and its energetic phenomena we propose to study (e.g. novae) of all sorts are natural laboratories of extreme physics that have direct consequences for understanding of plasmas and other technologies integral to propulsion in aeronautics. A theory of nonlinear wave breaking would have far-reaching consequences in turbulence study and atmospheric sciences. Finally, the observation of our predictions could shed light on atmospheric optics, whether as a use for calibration or understanding contamination effects.

References

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