Using MHD Codes to Simulate Compact Star Mergers

or, Two Become One: Magnetohydrodynamic Boogaloo

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The Big Picture

- Stars are the building block of the baryonic universe
- Our models of the universe are highly dependent on the evolution of stars, and importantly, interactions between stars
- We are concerned with White Dwarfs (WDs) and the stellar mergers they can be involved with

Figure: The famous "Horsehead" Nebula, part of a large complex of stellar nurseries approximately 1500 lightyears away. Source: *B33, The Horsehead Nebula*

Applications to Astrophysics

- Mergers between WDs and other stars (or WDs with themselves) are the suspected progenitor of Type Ia supernovae Kushnir et al. 2013. These supernovae are used to measure astronomical distances, so knowing their properties accurately is vital.
- Our models of Galactic Chemical Evolution have discrepancies to observations. Type Ia supernovae are a promising avenue to explain the differences Seitenzahl and Townsley 2017
- About 10% of stars (including WDs) have strong magnetic fields (10^6 to $10^9 G$), which are likely produced during stellar mergers *The Magnetic White Dwarfs – Open Issues*.

Applications to fusion energy

Prior studies into WD mergers often neglect much of the underlying physics. Recent studies of stellar mergers have started utilising more complete, 3D Magnetohydrodynamic simulations, but there still exists a gap in the research on WDs. Schneider et al. 2020; Schneider et al. 2019; Zhu et al. 2015

- Research into fusion and fusion plasmas has exploded over the last several decades, partially in response to the worsening environmental crisis caused by the human emission of fossil fuels into the Earth's atmosphere. As part of a wide-reaching response to this problem in the research community, much progress has been made in the designs of experimental fusion reactors.
- Much of the underlying fusion physics and physical constraints of the systems are analogous (e.g. in accretion disks)
- Conclusions about stellar stability could have applications for fusion research back in the lab.

Next Steps

The remainder of this thesis proposal review will consider the task of modelling WD mergers, what work has been done to this point and what is planned for the future.

- Section 2 will explore the relevant literature, including modelling a WD structure, introductory plasma fusion physics and prior work on compact object mergers.

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- Section 3 will discuss this project's specific research goals
- Section 4 will discuss progress over the last twelve months and a timeline for future milestones.

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The stellar life cycle

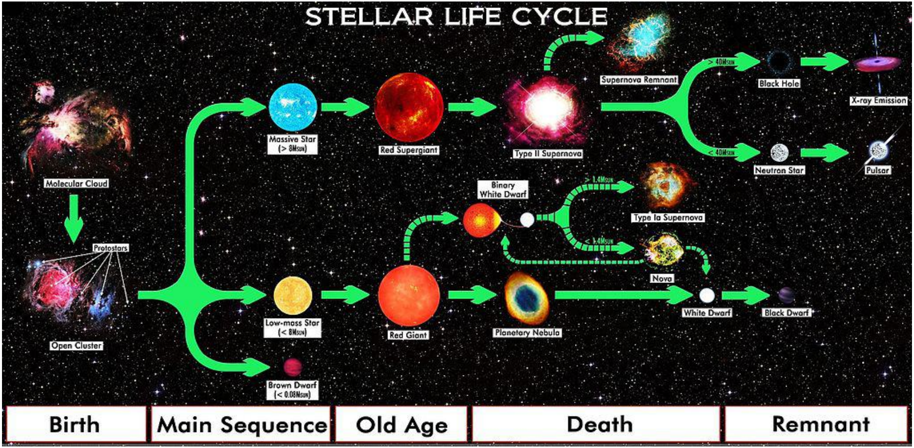


Figure: Our current model of the stellar life cycle. Source: Bailey 2017

What are White Dwarfs?

- Hot, dense core of a red giant after it blows away its outer layers as a 'planetary nebula'
- Temperature exceeds $T > 10^5 K$, and will generally cool and relax over the next 10^9 years. Generally 0.5 - 1 solar masses and a density of $10^9 kg/m^3$ *White Dwarfs*.
- Typically composed of Carbon, Oxygen, Helium, and Hydrogen (but Ne and Mg can be included too)
- 80% have H-dominated astmospheres. 16% have He McCook and Sion 1999

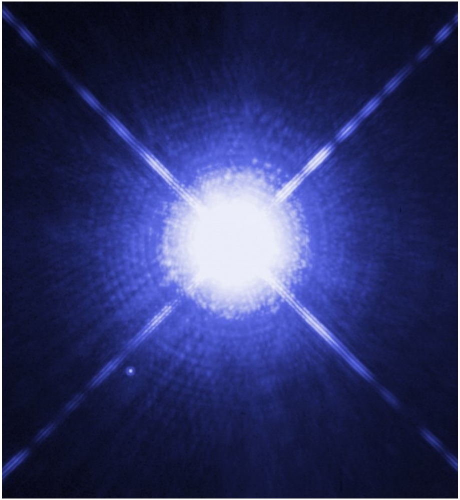


Figure: HST Image of Sirius A and B

WD Models

- In a WD, the force of gravitational collapse is opposed by "electron degeneracy pressure"
- This pressure is a macroscopic consequence of Quantum Mechanics
- The Pauli Exclusion Principle prevents electrons from occupying the same energy state so electrons must fill higher energy states, resulting in higher speeds resulting in a pressure that opposes gravity
- As the mass of a WD approaches its maximum value, electron speeds approach c.

Polytrope Models can also be used to model WDs. These simplified solutions assume a power law relationship between pressure and density which must hold throughout the whole star. This gives the Lane-Emden Equation.

$$\boxed{\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right)+\theta^n=0}$$

The Chandrasekhar Mass

Both the degenerate mass model and numerical solutions to the Lane-Emden equation predict that the mass of a WD will approach some maximum value. This is the **Chandrasekhar Mass**, and it represents a mass limit on the stability of the WD structure.

$$\boxed{M_{chand} \approx 1.4 M_\odot}$$

Beyond this limit, the WD structure cannot be supported by electron degeneracy pressure and collapses into a neutron star or detonates. This mass limit is what makes studying WD mergers so interesting!

WD Mergers

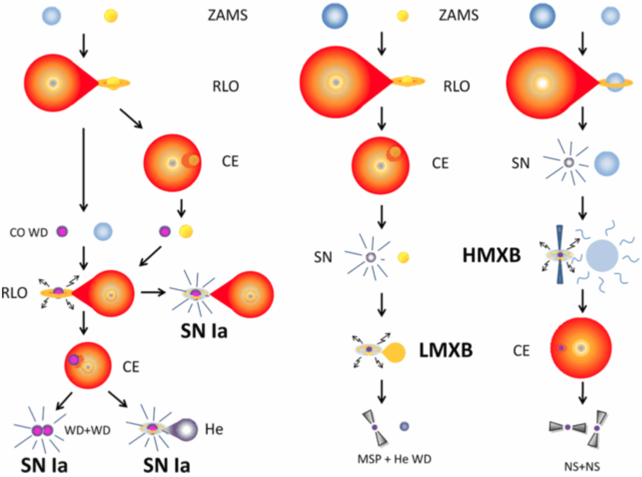


Figure: Merger pathways for compact objects. Source: Ivanova et al. 2013

Cataclysmic Variables (CVs)

- Stars begin their life at the Zero Age Main Sequence (ZAMS)
- CVs include a degenerate star and a low-mass companion whose gas is weakly bound
- The gas experiences Roche Lobe Overflow (RLO) and begins to acrete onto the companion
- The two stars might experience a Common Envelope (CE) phase
- The hot accretion disk can trigger nuclear reactions, causing a Thermonuclear runaway (Supernova)

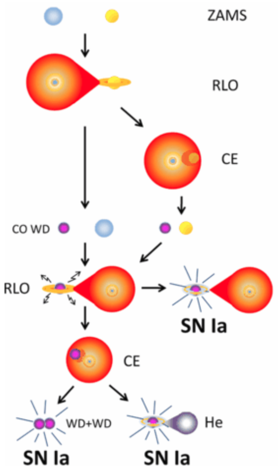


Figure: Merger pathways for WDs. Source: Ivanova et al. 2013

Modelling the accretion disk (α viscosity)

While the accretion disk is a common feature of many astrophysical systems, the question remains as to how angular momentum is being transported outwards, allowing matter to spiral inwards in a disc. This mechanism is usually called 'viscosity'. Shakura and Sunyaev were the first to propose a model for accretion disk viscosity Shakura and Sunyaev 1973. They argue based on energy conservation that radial effective temperature is distributed independently of viscosity:

$$T(R) \propto R^{-3/4}$$

They devise a dimensionless scaling of the kinematic viscosity

$$\nu = \alpha c_s H$$

where c_s is the local mean sound speed on the disc and $H \tilde{(} c_s / v_\phi) R$ is the scale height perpendicular to the disc plane at radius R where v_ϕ is the azimuthal velocity. α is dimensionless and specifies the local rate at which angular momentum is transported.

WD-WD Mergers and detonations

- WD-WD mergers follow much the same pattern. Here, the mass ratio is closer to one but the merger still involves an exchange of mass. Accretion of mass close to the Chandrasekhar limit destabilises the WD structure.
- The detonation is triggered by ignition of Carbon close to the core or possibly Helium, close to the surface. (Dessart et al. 2007; Saio and Jeffery 2002)
- Because the object is supported to electron degeneracy pressure, the whole structure is susceptible to thermonuclear runaway (i.e. supernovae Type Ia). This is because the degenerate electrons have a very small heat capacity.

Previous Studies of Mergers I

Several prior studies have investigated this or similar questions.
Schwab et al. 2012 used the HD code ZEUS-MP2 to simulate mergers for several different binary systems. The team tested CO-CO, He-CO and He-ONeMg systems and found significant variation in the results of their simulations between the different compositions. Schwab et al. found relatively robust results when examining CO-CO systems using their method; in this case they found that the Magnetorotational Instability (MRI) lead to enchanced viscosity. While the viscosity was enough to cause instabilities, Schwab et al. did not observe a thermonuclear runaway. They conclude:
"Our purely hydrodynamic simulations cannot address the effects of magnetic fields. MHD simulations resolving the action of the MRI would allow for a more realistic treatment of the viscous stresses than an α-viscosity..."

Previous Studies of Mergers II

Schneider et al. 2019 did conduct 3D MHD simulations on two higher mass (core hydrogen burning) stars. These stars, which are 8 and 9 solar masses respectively were shown in simulations to produce large magnetic fields via the MRI. Schneider et al. report that this merger remnant is likely to be a progenitor of a highly magnetic neutron star (a magnetar) and that their supernovae would be affected by the strong magnetic fields . Schneider et al. solves a discretised version of the MHD equations implemented by the moving mesh code AREPO, which will be discussed in the next section.

Previous Studies of Mergers III

Zhu et al. 2015 also examine mergers of Carbon-Oxygen WD binaries of 0.6 solar mass (i.e. a sub-Chandrasekhar mass merger). These mergers were also simulated in AREPO but in a 2D axisymmetric scenario. The group observed strong magnetic fields formed as a result of the MRI. However, the group suggests that their results are highly sensitive to the initial hydrodynamic conditions and that these might have artificially high core temperatures. They add that much of the behaviour of the non-axisymmetric remnant core they observe cannot be captured using a 2D coordinate system. Zhu et al. conclude their study by stressing: "... the need to perform high-resolution three-dimensional simulations of post-merger evolution to determine the final fate of the remnant."

The Bottom Line?

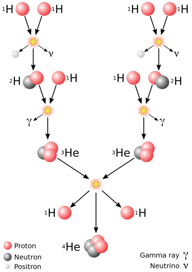
There is a gap to be filled

Previous studies have not incorporated the full complexity of 3D MHD to studying mergers and there are open questions to answer. At a minimum, our further research should investigate:

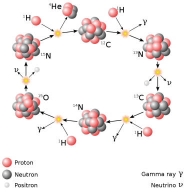
- More realistic WD chemical structures. This is necessary to ensure we capture the necessary nuclear reactions to achieve thermonuclear runaway.
- The MRI. This plays an important role in magnifying magnetic fields.
- Full 3D simulations to the extent possible.
- The AREPO moving mesh code.

MHD and Plasma properties

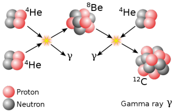
The difficulty here lies in the underlying complexity of the equations. One method of simplifying these general interactions is to single out the most common fusion reactions and formulate them in terms of known reaction rates. Three of the most relevant fusion processes for stellar fusion are the Proton-Proton (P-P) Chain, CNO Cycle and Triple-α process.



(a) P-P Chain. Source: *Astronomy:Proton–Proton Chain Reaction - HandWiki*



(b) CNO Cycle. Source: Borb Unknown dateUnknown date



(c) Triple-Alpha process. Source: assumed 11 April 2006 (original upload date)

MHD instabilities

Another important contribution which studying MHD can make to understanding these dynamics is in terms of instabilities.
One key process is the Magnetorotational Instability (MRI). This is triggered when fluid parcels rotate around a central body and are coupled by a magnetic seed field. The different radii mean that the two fluid parcels have different tangential velocities. The disk rotates differentially, causing the following loop:

1. Connected fluid elements have some initial displacement
2. Differential rotation increases the displacement, and tension causes the inner parcel to slow down, and the outer parcel to speed up
3. This transfer of angular momentum causes the inner parcel to migrate inwards and the outer parcel to be pushed outwards. Balbus and Hawley 1991.

MRI Diagram

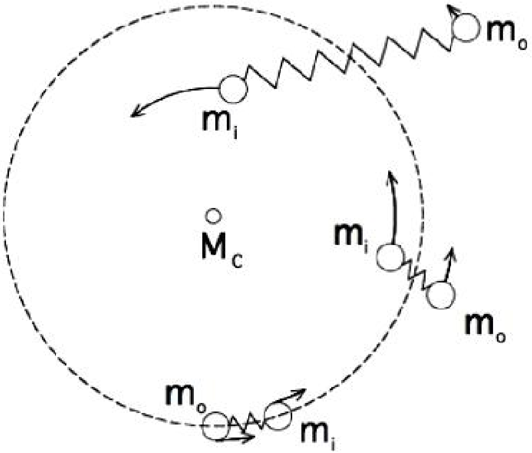


Figure: Diagram illustrating the Magnetorotational Instability. Source: Ji et al. 2006

Simulation Ingredients

Now that we have an understanding of the intricacies of the task of modelling compact object mergers, we must consider the question of how to make observations about such systems. Many of the equations of MHD cannot be solved analytically even for the most simple physical situations. Thus, we must turn to numerical methods. By discretising these continuous problems and encoding the analytical models into computers, we are able to create simulations that allow us to examine the relevant behaviour. High Performance Computing (HPC) allows us to achieve good resolutions even in these cases by taking advantage of clusters of computational resources and executing code in parallel. This section discusses some of the most relevant computational tools to our research problem.

N Body Simulations

N-body simulations allow us to simulate the dynamical behaviour of our merger system under the influence of gravity. The code being used for this purpose is the massively parallel MHD/gravity simulation code AREPO, which is designed for use in astrophysics. It employs a finite volume approach with a Voronoi mesh to solve a discretised version of the equations of hydrodynamics. A tree-particle mesh has been used to model the gravitational interactions and reduce the complexity of the many-particle simulations. Weinberger, Springel, and Pakmor 2020

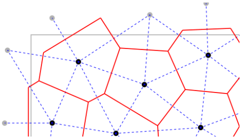


Figure: Voronoi mesh Weinberger, Springel, and Pakmor 2020

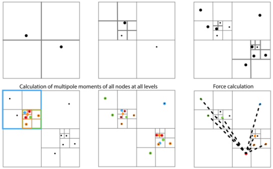


Figure: Particle Tree Weinberger, Springel, and Pakmor 2020

Plasma Equilibrium and Stability

FINESSE is a tokamak modelling code which is designed to model situations which can be described by axisymmetric force balance. This situation can be described using a combination of cylindrical coordinates (R, ϕ, z) and simple toroidal coordinates (r, θ, ϕ) where

$$R = R_0 + r\cos\theta; \quad z = r\sin\theta$$

FINESSE then solved a modified version of the Grad-Shafranov Equation (GSE):

$$\nabla\cdot\left[\frac{1-\chi'^2/\rho}{R^2}\nabla\psi\right] + \left(\frac{\chi'}{\rho R^2} + v_\phi B_\phi\right)$$
$$-\frac{1}{\gamma-1}\rho\gamma S' + \frac{B_\phi}{R}I' + \rho R v_\phi \Omega' = 0$$

where $' \equiv d/d\psi$. FINESSE then solves a version of this problem using efficient eigenvalue methods Beliën et al. 2002.

Stellar Structure Codes

Modules for Experiments in Stellar Astrophysics (MESA)

- Temporal evolution of stars in 1D
- Able to simulate nuclear reactions
- Able to simulate accretion

White Dwarf Evolution Code (MESA)

- Able to simulate WD internal chemical structure better than polytrope models
- Takes properties of WD (e.g. mass, effective temperature) and produces 1D radial abundance profiles

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Overview

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- Stability analysis of accretion disk
- Exploration of flow regime changes
- Application of astrophysical models to a fusion energy context

Creating a WD internal structure

Without a realistic WD structure, there can be little confidence in the physical accuracy of the resulting merger product. Thus, the most important research goal is to generate a realistic WD chemical structure and express these results in a form which can be simulated over time.

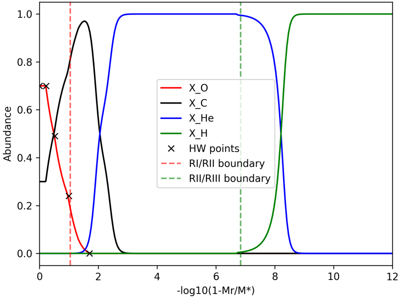
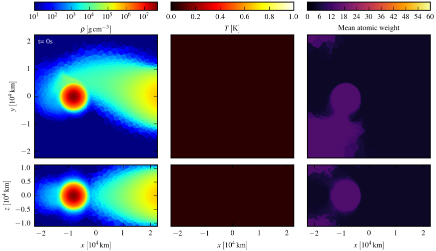


Figure: WD abundance profile

Modelling time evolution of merger scenarios

Having generated a realistic structure, the next most important step is to model the time evolution of our stellar progenitors. This will involve simulating merger interactions over a wide variety of of mass ratios, total masses, chemical compositions and initial displacements.



(a) Time evolution results from AREPO

Stability analysis of accretion disk

Some prior work has been done in this field, notably by Doak 2018. Doak aimed to apply FINESSE to tokamak plasmas and accretion disks, and was able to express the central mass of the accretion disk in a form required by FINESSE but was lacking additional boundary information. This boundary information will be specified by the prior time evolution simulations. Additionally, Blokland began a preliminary stability analysis using a spectral code PHOENIX. This code is poloidal-flow enabled but no results were presented by Blokland using poloidal flow (Blokland, Keppens, and Goedbloed 2007).

Flow regime changes

There is a natural extension to this work in that FINESSE can include poloidal flow in its MHD model. This gives an obvious opportunity for adding new physics to our models. One starting point would be to explore under what poloidal flow regime the ODE changes from elliptic to hyperbolic, and how this changes the numerics of the simulation. This new physics might also provide valuable insight to astrophysical scenarios too, such as when the mass of the donor star in a binary increases to approach a mass ratio close to one.

Knowledge transfer - astrophysical and fusion energy

Lastly, it is hoped that the results provided by the astrophysical merger simulations will yield some insights into accelerating the pace of development of fusion research in the lab.

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Experimentation with FINESSE and PHOENIX

During this initial phase of the project in April 2020, the MHD simulation codes FINESSE and PHOENIX were investigated to determine their applicability to the modelling problem. Several weeks were spent obtaining the correct software and libraries to run simulations using these codes. Once set up, FINESSE/PHOENIX were used to replicate well-documented results from several papers to ensure the software was working correctly Beliën et al. 2002; Blokland 2007.

Simplified merger scenarios on NCI

When preparing to simulate the time evolution of the compact star scenario, it was found that FINESSE and PHOENIX did not have the capability to model time evolution, so this time is being spent investigating other MHD codes to determine their applicability. Several alternatives were investigated based on criterion including: execution speed, ease-of-use, extensibility, existing capabilities and what language the code is written in. It was decided that AREPO had the best combination of characteristics Weinberger, Springel, and Pakmor 2020. Having identified the best tools for modelling, this phase involved constructing a model for a single compact star, then multiple compact objects.

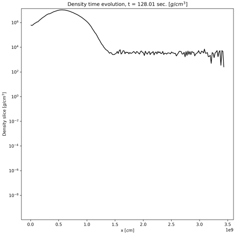
One issue with these simulations was that the merger remnants never reached the critical temperatures and pressures necessary for AREPO's nuclear network to activate. This is what motivated a shift to creating a more realistic WD internal structure.

Experimentation with WDEC

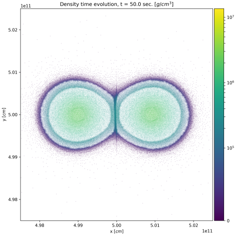
As a result of the lack of adequate temperatures and pressures, it was decided to revisit the WD structure. The justification was that many WDs are not composed purely of Carbon and Oxygen but instead have Helim and Hydrogen shells - perhaps the incorporation of these lighter elements would be sufficient to tip over the temperature and pressure threshold required for fusion, starting a thermonuclear runaway. Much of this time was spent working with the WDEC software to understand its inputs and outputs; eventually, a structure was generated and mapped from 1D to 3D using a HEALPIX mapping (*Jet Propulsion Laboratory HEALPix Home Page*).

Development of AREPO Helper software

Some time was also spent creating helper software to interface with the input and output files from AREPO simulations. These 'snapshots' contain enumerations of the particular particles and their position, velocity, temperature etc. at any given timestep. This was a very unhelpful format to understand the merger dynamics, so some Python code was written to create plots, animations and radial slices of the 3D simulation space. This allowed for more accurate estimation of the important quantities and provided insights into the shape of the overall structure.

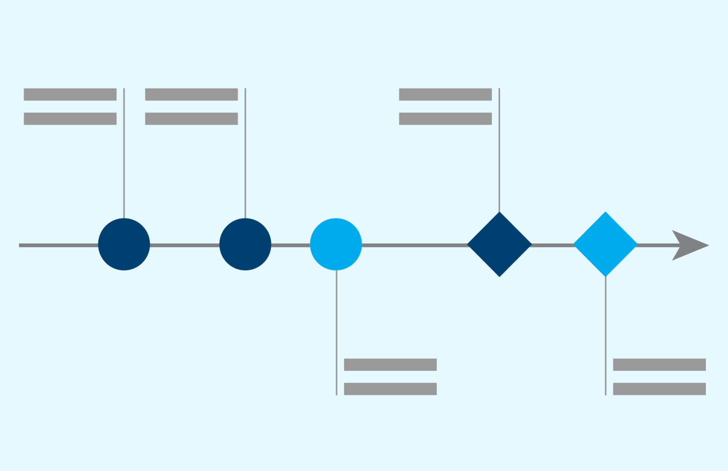


(a) Radial density slice



(b) Density scatter plot

Timeline for future work



MODELLING I - April to June 2021

- *Outline:* During this phase, more time will be spent investigating the numerical errors caused by using WDEC-produced structures as input to AREPO. This will involve experimentation with different AREPO compiler and run options. Once this issue is resolved, it should be possible to conduct further simulations using the WDEC structure. It is hoped that this will be enough to prompt nuclear reactions in simulation. If this does not occur, this plan will need to be reviewed.
- *Progress:* This phase is ongoing

MODELLING II - June to August 2021

- *Outline:* During this phase, time will be booked on the National Computational Infrastructure (NCI) to conduct the large-scale merger simulations. Time will be devoted to examining the results and returning to conduct further simulations if necessary. In particular, this will involve examining under what conditions poloidal flow in the simulations transitions from elliptic to hyperbolic and what effects this has. This phase will also include investigation of the long-term stability characteristics of compact star accretion disks.
- *Progress:* This phase has not been started.

VALIDATION - August to November 2021

- *Outline* During this phase, simulation results will be compared to observational data and models in the literature related to compact star merger events and accretion disks. Some additional simulation time will be devoted to replicating results from the literature as a sense-check. Where results diverge, time will be devoted to understanding the differences. These results will be applied to a tokamak fusion context by cross-validation of the results using FINESSE and PHOENIX.
- *Progress:* FINESSE and PHOENIX have already been set up for cross-validation. Additionally, some time was spent making an installation guide which should simplify the process of installing FINESSE and PHOENIX on NCI if need be.

EARLY PUBLICATION - November 2021 to January 2022

- *Outline:* During this period, time will mostly be devoted to drafting and refining results for publication.
- *Progress:* This phase has not been started.

EXTENSION - January to March 2022

- *Outline* Having completed initial publication, this time will be spent generalising the results by relaxing the simulation constraints and determining if the results still make sense. This time will also be spent finding further areas of overlap with the fusion energy research context.
- *Progress:* This phase has not been started.

Conclusion

Mergers of WDs are an important research question that has applications to both astrophysics and fusion research. Better understanding of mergers will have downstream consequences for:

- Our understanding of Supernova Type Ia, and thus GCE
- Formation of highly magnetic stars
- Understanding flow in fusion reactors

Gaps exist in the research to account for complex 3D MHD effects. Simulations using AREPO will allow us to study the time dynamics whereas FINESSE and PHOENIX will allow for more detailed study of flow and stability. WDEC will allow for simulation of more realistic internal structure. Future work will involve simulating mergers for a number of mass ratios, compositions and total masses.

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