■ Scientific Justification

[LC: Copied from HST website for reference, will be removed:] *AR Proposals should describe how the project improves upon or adds to the previous use of the data. Theory Proposals should include a description of the scientific investigation that will be enabled by the successful completion of the program, and their relevance to HST.*

1 Background

Common envelope evolution (CEE) is a strongly interacting phase of binary stellar evolution whose consequences are fundamental to understanding the end states of solar mass stars (planetary nebulae), the progenitors of supernovae type Ia, the progenitors of compact binaries that become gravitational wave sources, as well as various classes of optical and infrared transients. CEE occurs when a binary orbit decays to the point that the secondary plunges into the envelope of the primary (Fig. 1: Paczynski 1976). Dissipative losses drive a fast inspiral of the secondary leading to the ejection of the envelope or to a merger of the secondary with the core of the primary. A handful of common envelope (CE) events have been observed directly as luminous red transients (LRN; Martini et al., 1999) and intermediate luminosity optical transients (ILOT; Kasliwal, 2012), and these are being discovered at an increasing rate in the Milky Way and nearby galaxies (Kasliwal et al., 2017) due to continual improvements in observational instruments and techniques. Archival data from the *Hubble Space Telescope (HST)* has played an important role in understanding the progenitors of these transient events (e.g. Williams et al., 2015). *HST* has also been crucial for studying their light echoes (e.g. Bond et al., 2003).

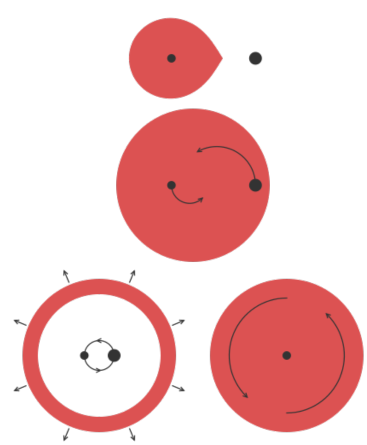

Figure 1: Schematic of common envelope evolution which occurs when a binary orbit decays to the point that the secondary plunges into the envelope of the primary, expelling the envelope leading to a tight binary or else merging with the giant's core.

2 Past work

Understanding CEE requires simulating a wide, dynamically coupled range of physical processes and scales in 3D. Until recently there have been few numerical studies of CEE and the majority of these have employed smooth particle hydrodynamic techniques (see Iaconi et al. 2017 for a comprehensive list of CE simulations from the literature). Only in the last few years have grid based codes (adaptive mesh refinement (AMR) in particular) tackled the problem. Recent advances in numerical modeling however, now allow the CEE problem to be more fully addressed. However, modeling of RLN or ILOT events has been limited to analytic estimates (MacLeod et al., 2017), estimates based on, but not directly calculated from, results of low resolution CEE simulations (Ivanova et al., 2013; Nandez et al., 2014), or simulations that can capture only the phase that precedes the CE phase (Pejcha et al., 2017; Metzger & Pejcha, 2017). An exception is the work by Galaviz et al. (2017), which obtained mock light curves and images directly from a CEE simulation (see also Reichardt et al., 2019). However, this work was an exploratory demonstration not focused on explaining a particular transient event, and principally serving to identify the various challenges involved in predicting observable results from global 3D hydrodynamical grid-based CEE simulations. Lessons learned from this work will allow us to make progress, now using a more powerful AMR-based CE simulation platform.

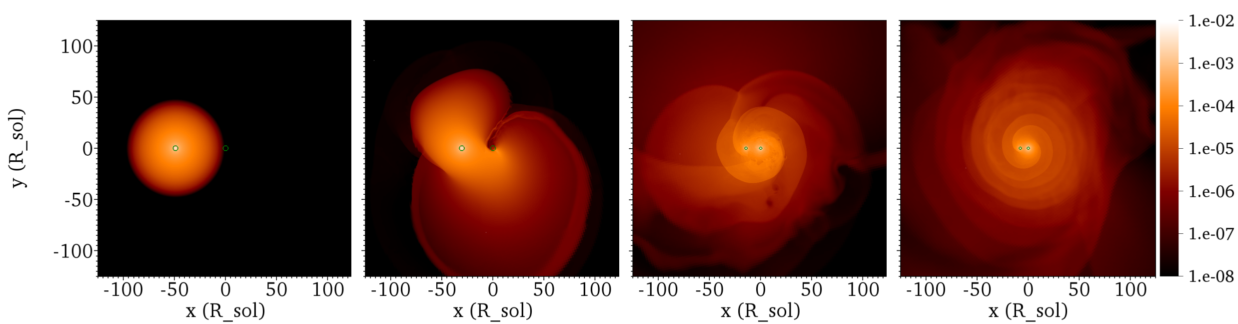

Figure 2: Density, in $\mathrm{g\,cm^{-3}}$ in a slice through the secondary and parallel to the xy (orbital) plane, for the fiducial model (no subgrid accretion). The secondary is positioned at the centre with the frame rotated so that the primary particle is always situated to its left (the plotted frame of reference is rotating with the instantaneous angular velocity of the particles' orbit). Both particles are denoted with a green circle with radius equal to the spline softening length. Snapshots from left to right are at $t = 0$, 10, 20 and 40 d. Axis units are $\mathrm{R_\odot}$.

3 Summary of Proposed Methods

We have built a CE simulation module in the fully-parallelized AMR multi-physics code AstroBEAR (?). This code has now been used to invesigate accretion in CEE (Chamandy et al., 2018b), the global CE energy budget , and the relative motion between the secondary and primary cores and envelope gas (Chamandy et al., 2018a). An example of results from one of our simulations is shown in Fig. 2, where we plot snapshots of gas density in the orbital plane. Our simulations can overcome many of the technical limitations identified by Galaviz et al. (2017), partly owing to the very high resolution and numerical accuracy afforded by AMR and the availability of world-class computational facilities, and partly owing to new physics capabilities and refined numerical methods.

4 Scientific Goals

We propose to use the AMR MHD multi-physics CE code AstroBEAR to obtain mock light curves and 2D intensity maps resulting from CE events. Our simulations will directly model progenitor systems of RLN and ILOT transients (those known already as well as future discoveries) as they evolve through the transient phase and beyond. Physically, we will model the late stages of Roche lobe overflow (Reichardt et al., 2019), through the dynamical plunge-in phase, up to the late stages of common envelope inspiral. These mock light curves will be compared with light curves of specific transients obtained from various instruments, along with their pre- (when available) and post-burst light curves from *HST* data. The ultimate aim is to constrain CE models using these comparisons, and then to apply these improved models to explore the parameter space and make predictions for future transient events, and, more generally, to understand CEE for a variety of systems including the progenitors of gravitational wave sources.

Analysis Plan

[LC: Copied from HST website for reference, will be removed:] *Theory Proposals should discuss the types of HST data that will benefit from the proposed investigation, and references to specific data sets in the HST Data Archive should be given where possible. They should also describe how the results of the theoretical investigation will be made available to the astronomical community, and on what timescale the results are expected.*

1 Description of the Code

AstroBEAR uses a hierarchical approach to parallelization suitable for multicore architectures in which large-scale patches of data are distributed to nodes using MPI and the work for an individual patch is distributed across the cores on a node using OpenMP directives. AstroBEAR also employs new techniques such as load balancing by threading the grid advances on each level with preference going to the finer level grids. The multi-physics capabilities of AstroBEAR have been significantly expanded by including solvers for elliptic and parabolic equations. Adapting the linear system solver HYPRE, we now routinely simulate systems in which self-gravity, heat conduction, magnetic resistivity and radiation transfer are important. In addition, AstroBEAR can treat gravitationally interacting point particles which accrete mass.

2 HST Data Sets

3 Proposed Timeline

The project will consist of four phases, each lasting about one year, for a total project time of four years:

(i) Implementing, testing, and optimizing the mock data production pipeline.

(ii) Performing one or more high resolution simulations that model one or more observed transients, obtaining simulation mock data products, and comparing these mock data products with observed data.

(iii) Developing the code to add more physics, including sophisticated 3D radiation transport, and implementing tabular equations of state that will allow recombination and convection to be accurately modeled.

(iv) Exploring the parameter space of stellar merger events using this optimized version of the code, and making predictions for future observations.

We briefly discuss each of these phases below.

3.1 Mock Data Production Pipeline

The first step will be to implement an approach similar to that of Galaviz et al. (2017) into our AstroBEAR CE simulation platform. They identified two main challenges, namely adverse effects of the artificial hot ambient medium used to stabilize the initial star, and extreme temperature gradients in the photosphere which could not be resolved. Both of these limitations are expected to be much less severe in AstroBEAR, where the highest resolution is generally about 20 times higher than in that preliminary study. With a higher resolution at the surface of the star at the beginning of the simulation, the initial primary star is less prone to numerical instability, and the temperature of the ambient medium can be reduced somewhat. This is also aided by employing a sophisticated method to stabilize the initial star prior to setting the binary system in motion (Ohlmann et al., 2017), which is already being used in AstroBEAR CE simulations (Chamandy et al., 2018b).

To obtain accurate 2D intensity maps which can be integrated to obtain the associated light curve, the photosphere will be calculated with the help of an opacity table (Galaviz et al., 2017). We also plan to then use the tool SHAPE (successful application of this software to visualize AstroBEAR simulation output has recently been achieved) to 3D render the phostospheric surface. We will then integrate the intensity to obtain an overall flux, assuming a blackbody spectrum, and, finally, we will plot the apparent magnitude in various frequency bands as a function of time. We will also produce movies of the photosphere intensity and many other relevant diagnostics using SHAPE and VisIt software. All of these will be included in online repositories referenced in the publications.

3.2 Comparison of a Simulation with an Observed Transient

The most natural choice is the stellar-merger transient M31LRN 2015, discovered by the MASTER network (http://observ.pereplet.ru), for which *HST* data is available for both the pre-outburst and post-outburst source (see MacLeod et al. 2017 for a review). Fig. 3 (right panel) shows light curves from the transient source which combines data from two sets of observations, while the left panel shows *HST* data from the progenitor system, overplotted on stellar evolution models from Modules for Experiments in Stellar Astrophysics (MESA) 1D simulations (adapted from MacLeod et al. 2017). If time permits, we will also simulate the well-studied Galactic transient V838 Mon, whose subsequent light echo was imaged by *HST* from 2002-2008 (Fig. 4: Bond et al. 2003)

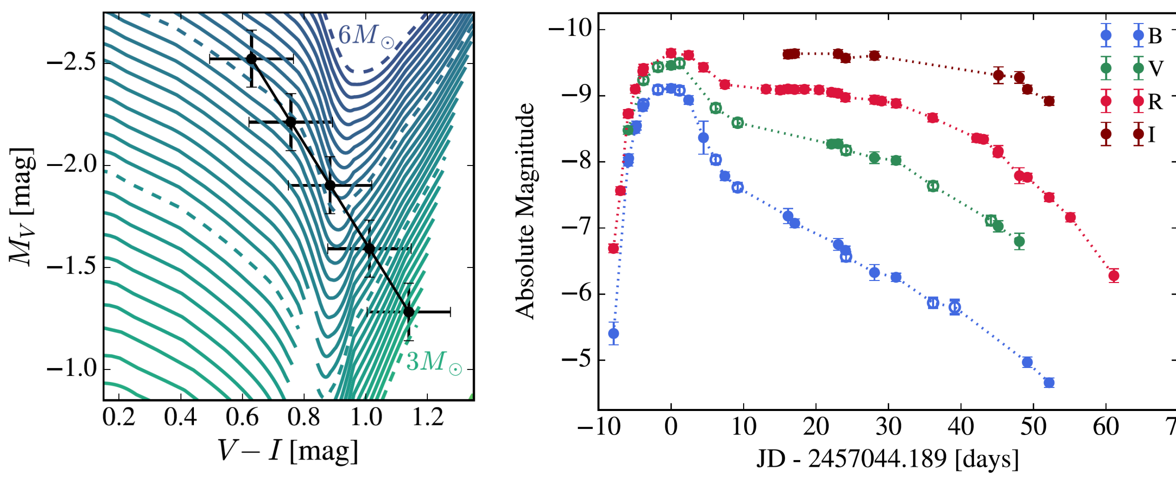

Figure 3: caption

3.3 Adding New Physics

Our CE AstroBEAR module takes as input the output of a 1D (spherical) stellar simulation which we perform using MESA. Currently, we extract density and pressure profiles from MESA and employ an adiabatic ideal gas equation of state. We have started working on implementing the more realistic tabulated equation of state employed in MESA. This is expected to result in convective layers in the initial primary envelope (Ohlmann et al., 2017), and convection is predicted to have important effects on CEE and its observational signatures (e.g. Wilson & Nordhaus, 2018). Implementing a tabulated equation of state also allows for the energy released locally by recombination of ionized gas to be included in the

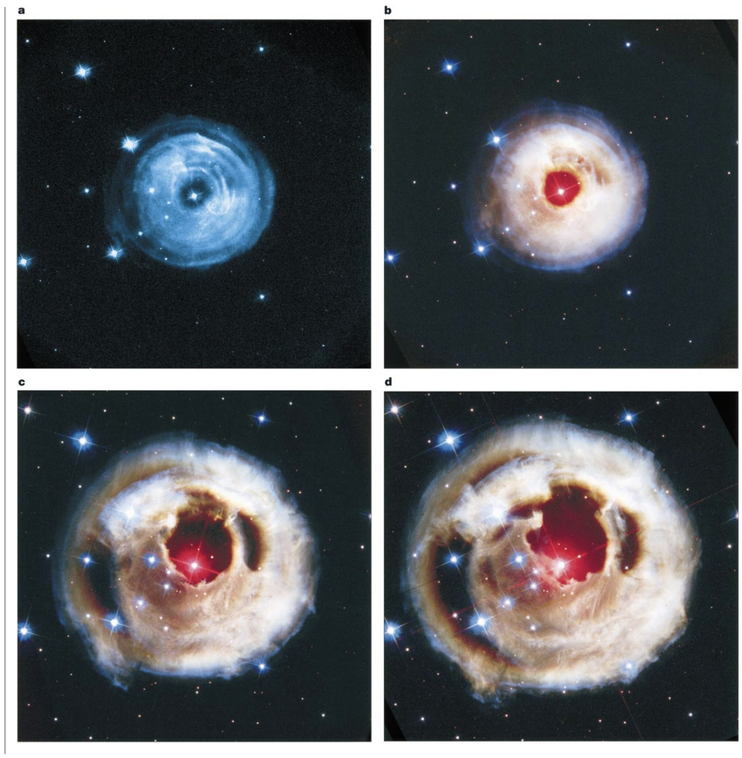

Figure 4: caption

simulation, which may have important observational implications (Nandez & Ivanova, 2016). Finally, and most importantly, we will complete the development of 3D radiation transport, extending the current 2D flux-limited radiative diffusion implementation. This will allow us to predict the location of the photosphere (optical depth $\tau \sim 1$) to high accuracy.

3.4 Exploring the Parameter Space

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