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Concise Research Statement

In general, I am eager to understand all phenomena involving complex fluid flows—turbulence, convection, jets, etc.—and thermonuclear reactions. My current area of research involves simulating various explosive astrophysical phenomena along with the low Mach number convective burning leading up to the explosion. Currently, I am investigating three different explosive phenomena: 1) surface convection leading up to runaway in X-ray bursts (XRBs), 2) surface convection leading up to runaway in sub-Chandrasekhar mass models for Type Ia supernovae (SNIae), and 3) convective ignition and propagation of a flame in Chandrasekhar mass SNIae.

X-ray Bursts

An XRB is essentially the analogue of a recurrent nova, except on the surface of a neutron star. The strong gravitational field compresses the accreted H/He into a layer with thickness $\sim$ 10 m; at the base, the compressional heating raises the temperature high enough to begin fusion. After a short period of convection, a thin-shell instability creates a localized thermonuclear runaway that sparks a deflagration (or flame), which propagates around the star in about a second. After the system has settled, accretion continues and the process occurs again on timescales of days to a week making XRBs *the* most frequent thermonuclear explosions in the Universe. Furthermore, for very events exceding the local Eddington luminosity, it is possible—if the distance to the source is known—to infer the mass and radius of the underlying neutron star.

In practice, there are many unknowns that make it difficult to determine these neutron star properties. For instance, it is not well known how ignition occurs: is it local to a single point or are there multiple hot spots that trigger thermonuclear runaway? What is the state of the material in which the burning front propagates? Many of these problems are inherently multi-d; for instance, convective mixing helps sets the composition and opacity of the atmosphere and can only be properly treated in multidimensional simulations. The high sound speed near the base of the accreted layer causes the convective velocities to be only a few percent of sonic up until runaway. This severely limits the stable (CFL) timestep size for a traditional explicit compressible hydrodynamics code.

To work around this computational limitation, I've used the low Mach number approximation code Maestro (Maestro paper in publication list), which decomposes the pressure field into a hydrostatic base state that governs the thermodynamics and a local perturbational pressure field that governs the dynamics of the system. In this way sound waves are filtered from the system and the characteristics of our equation set are changed such that the Courant condition limits our timestep size based on the dynamics and not the accoustics. Furthermore, we retain various compressible effects such as those due to thermal diffusion, compositional change, and stratification.

I've studied both XRBs that accrete pure helium, which have simple alpha-capture reactions (XRB paper; Ph.D. thesis), as well the longer duration mixed H/He-burning XRBs, which have more exotic nuclear reactions including the rp-process (thesis; paper in prep). These are the most realistic multidimensional hydrodynamic simulations of XRBs in the literature and ran on up to 1000 cores using only MPI for parallelization. One key finding we have found is that the thin burning region requires rather high (0.5 cm zone^{-1}; a factor of 10 higher than any other multidimensional model to date) resolution for any sort of convergence of the energy generation and/or the amount of convective undershoot. Furthermore, while we have not yet simulated all the way to runaway, we have shown that in two dimensions, there is sufficient entrainement of the underlying neutron star material, which we took to be ^{56}Fe, to possibly alter both the conductivity (important for flame propagation) and overall composition near the photosphere (important for using these to infer neutron star properties).

Sub-Chandrasekhar Mass Supernovae Models

The sub-Chandrasekhar mass model for SNIa is somewhat similar to the XRB situation except the neutron star is now replaced with a $\sim$ 1 $M_\odot$ C/O white dwarf and the accreted layer is pure helium. Furthermore, the runaway ignition in the sub-Chandra SNIa model is thought to be a detonation wave in the helium layer that may or may not launch a shock into the core causing a carbon detonation. Again, prior to runaway, burning at the base of layer drives subsonic convection, and it is unknown exactly how the ignition occurs.

Using Maestro, we've performed the first multidimensional simulations of the convection leading up to runaway, using a simplified 1 $M_\odot$ white dwarf plus a 0.05 $M_\odot$ helium layer (sub-Chandra paper). With the lower surface gravity compared to the neutron star, the helium layer is less compressed and allows for much coarser resolution and hence 3d. That first paper was more of a proof of concept, however we were able to run that model until the burning went highly nonlinear and the Mach number of the flow became too large for the low Mach number approximation to remain valid. Nevertheless, this model exhibited well defined convective cells that had a radial extent somewhat greater than a pressure scale height, which is what is assumed in most 1d models using MLT. Furthermore, even though we had numerical "ignition" in a single cell, there were several localized hotspots that approached very near runaway conditions suggesting that multiple ignition points may be possible in a stochastic nature. More work is needed and currently underway to further investigate these claims as well as the effects of different white dwarf masses and helium shell masses. These simulations used both MPI and OpenMP parallelization and ran on a few thousand up to 10,000 cores.

Chandrasekhar Mass Supernovae Models

In the Chandra mass SNIae model, a $\sim 1.38\ M\odot$ C/O white dwarf accretes material from its companion until the core becomes compressed enough to trigger carbon fusion. This core burning drives subsonic convection for about a millenium before a runaway ignites a flame. Historically, this has been the favored model for explaining SNIae, and there has been extensive work on simulations over the last several decades. In the last 10 to 15 years three dimensional simulations have been performed, but due to the difficulties of modeling low Mach number flows, these simulations only considered the evolution *after* the flame had been ignited. There were very little constraints on where the intitial flame should be located or how large was the ignition kernel. Since they did not simulate the prior convection, these simualtions often place a flame in a static white dwarf background.

Using Maestro, we have performed the first three dimensional simulations of the (last few hours of) convection leading up to runaway (white dwarf convection paper). Similar to the sub-Chandra models, ignition occured in a localized region with other hot spots coming in and out of existence in a stochastic nature. However, unlike the sub-Chandra model, the other hot spots didn't approach nearly as close to the runaway conditions, thus indicating that ignition occurs at a single point. We showed that this likely occurs about 50 km off-center in a region that is moving radially outward; These simulations ran on about 12,000 processors (about the order on which Maestro scales well) using a hybrid MPI+OpenMP parallelization.

When ignition occurs in Maestro, the Mach number becomes too large for the low Mach number approximation to remain valid. To continue the evolution of the flame, we therefore turn to our explicit compressible hydrodyanmics code Castro. Both Maestro and Castro share the same underlying data structures so porting the data is fairly straightforward. However, these two codes solve fundamentally different equations, and Maestro's decomposition into base and perturbational states makes it a little bit tricky to ensure thermodynamic consistency when mapping over the data to Castro.

After overcoming the numerical difficulties of putting our ignition results into Castro, we have performed very high resolution (initially 135 m zone^{-1} with AMR) simulations of the propagation of the flame (paper in prep). In particular, we turned the $\sim 4\ \text{km}^3$ cube Maestro ignition point into a rough sphere of radius 2 km and turned the material inside the sphere into the hot ashes that would have resulted from the full flame burning. This hot spot buoyantly rises through the background convective flow field, developing Rayleigh-Taylor instabilities and experiencing strong amounts of shear.

Admittedly, we used a very simple flame model (constant speed) in this proof of concept study, but one of the interesting things that we found is that the background turbulennce field does not have a significant affect on the flame's evolution, if ignited where Maestro says it should ignite. However, if we arbitrarily move the ignition point closer to the center (a possibility given the distribution of hotspot locations from our Maestro studies), then the smaller buoyancy force lets the bubble stick around longer and the turbulence has more time to cause distortions of the flame surface. The total amounts of intermediate mass elements, iron group elements, and more importantly ^{56}Ni produced is dependent on these turbulence-flame interactions as well as the solid angle subtended by the initial ignition point. These simulations ran on $\sim$ 65,000 cores with five levels of refinement (Castro does sub-cycling in time) and again using a hybrid MPI+OpenMP approach.