3D SIMULATIONS OF I-PROCESS NUCLEOSYNTHESIS

Allocation: NSF PRAC/3,000 Knh
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EXECUTIVE SUMMARY

Our team is simulating brief events in the interiors of evolved stars that result in ingestion of unprocessed new fuel into convection zones above nuclear burning shells. The new fuel can burn very violently under the much hotter conditions in the convection zone after reaching a sufficient depth within it. This burning sets off a series of reactions that dramatically affects the nucleosynthesis of heavier elements and, hence, the ultimate expulsion of heavier elements into the surrounding interstellar gas. Expulsion can be either a relatively slow expulsion of the outer envelope of the star or by an explosion of the star itself, if it is sufficiently massive. This work involves large and very detailed 3D simulations of the entirety of the stellar interior, for which Blue Waters is ideally suited.

RESEARCH CHALLENGE

Our simulations involve brief but important events in the lives of stars that can greatly affect the heavier nuclei that the stars produce. We have been concentrating so far on hydrogen ingestion flashes in which unburned hydrogen-rich fuel is brought into the convection zone above the helium-burning shell. The ingested hydrogen reacts with carbon in the convection zone to set off a sequence of nucleosynthesis reactions that is called the i-process, since the neutron fluxes that result are intermediate between the slow and rapid s- and r-process nucleosynthesis. In the beginning of our project on Blue Waters, we simulated hydrogen ingestion events in evolved stars, and during the last year we have been gearing up to attack the more challenging problem of the potential merger of multiple nuclear burning shells in massive stars. This has involved detailed studies of the ingestion process, particularly in massive star contexts, as well as the aggressive development of a new simulation code. Our results on i-process nucleosynthesis are important as inputs for the study of the chemical evolution of galaxies. Our new work with massive stars, just begun, could have a large impact on the conditions just before those stars explode, and also on the injection of heavier elements from these explosions into the surrounding interstellar medium.

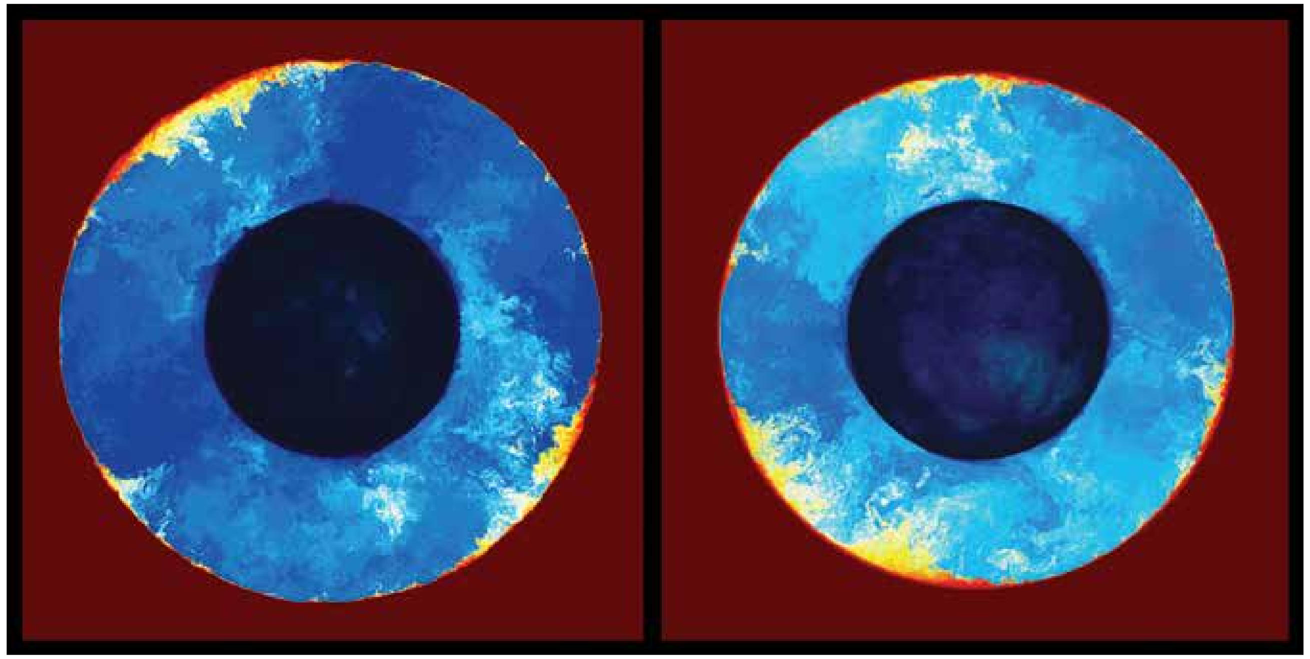

Figure 1: Snapshots of the distribution of ingested gas from above the convection zone generated by oxygen burning in model 25-solar-mass star. Left: 2.25x the luminosity of the 1D model. Right: 56.25x this luminosity to validate 1D descriptions of the ingestion phenomenon and to determine their dependence on parameters of the stellar context. Colors emphasize similarity of flows despite different velocities, time scales.

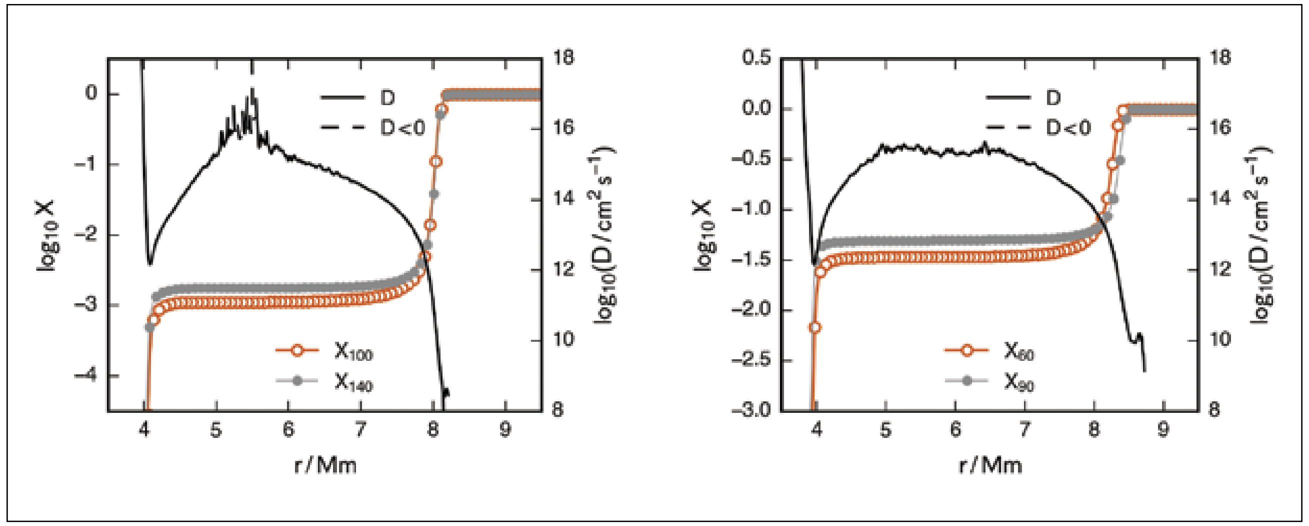

Figure 2: Effective diffusion coefficients in ID descriptions of 3D simulations of gas entrainment from above the convection zone generated by oxygen burning in model 25-solar-mass star. Left: 2.25x luminosity of ID model. Right: 56.25x this luminosity. Specialized simulations matching these parameters pinned down very small effective diffusion values in stably stratified gas regions.

METHODS & CODES

Our work to date simulating hydrogen ingestion flashes exploits the piecewise parabolic method (PPM) coupled with the piecewise parabolic Boltzmann (PPB) moment-conserving advection scheme for the multifluid volume fraction. PPB delivers more than double the resolving power of the PPM scheme for the single, very important variable representing the volume fraction of entrained fluid. Together with the already high resolving power of PPM, we are able to obtain very accurate results on a uniform grid. We must simulate a great many large-eddy overturning times in the convection zone above a nuclear burning shell in order to accurately approach a nonlinear, global oscillation of the burning of ingested hydrogen that increases the hydrogen ingestion rate by as much as two orders of magnitude. We are able to cover this long approach to the violent ingestion event because our PPM code scales to nearly 14,000 nodes on Blue Waters, at which scale it advances the simulation by roughly 20 time steps per second. Thus, the millions of time steps we need to simulate an ingestion event accurately are practical on Blue Waters with our code.

We have been turning our attention this year to massive stars, where the ingestion of material from above a burning shell of, for example, oxygen can allow the convection zone above that burning shell to eat its way outward in radius until it reaches the carbon-burning shell above it. A merger of these two burning shells can then result. Simulating this process is very challenging. We have been studying the relevant ingestion process in considerable detail over this last year with the goal of alternating between 1D and 3D simulation in order to span the time necessary in leading up to a shell merger. Our 3D simulations would keep models used in the ID intervals that stitch one 3D run to the next validated as good descriptions of the full 3D results. This work is illustrated in the Figs. 1 and 2.

We have devoted an enormous effort during the last year and a half to the development of a completely new code. This code adds a Level 3 adaptive mesh refinement (AMR) grid that will enable us to contain multiple nuclear burning shells and their respective convection zones in a single simulation. It is designed to scale to 14,000 nodes while running roughly twice as fast as our older code per node by exploiting 32-bit precision and GPU (graphics processing unit) acceleration [1–3].

Results & Impact

We are producing a database of detailed simulations that investigates the phenomenon of convective boundary mixing at unprecedented accuracy for convection zones that extend over ranges in radius of more than a factor of two (see www.lcse.umn.edu). Global convection modes play an important role in these situations, making simulation difficult and costly [4–6]. Convective boundary mixing plays an important role in stellar evolution. In particular, in ingestion events that we study, it can have a dramatic impact on nucleosynthesis, which in turn affects galactic chemical evolution [7].

WHY BLUE WATERS

We have carried out our simulations on Blue Waters because of its special ability to enable our simulation code to be run at a sufficiently large scale that our large computations can each be completed in less than one week [8]. This allows our team to pose questions and get answers on a timescale that is conducive to productive thought and dynamic adjustment of our research direction.

PUBLICATIONS AND DATA SETS

For publications, see reference list in back of book.
For shared data sets, see www.lcse.umn.edu.