3D STELLAR HYDRODYNAMICS OF H-INGESTION FLASHES AND SHELL MERGERS

Allocation: NSF PRAC/4,000 Knh
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EXECUTIVE SUMMARY

Our teams at the University of Minnesota, led by PI Paul Woodward, and at the University of Victoria, led by collaborator Falk Herwig, are simulating brief events in the interiors of evolved stars that result in the 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, affects the ultimate expulsion of heavier elements into the surrounding interstellar gas, either by 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 detailed 3D simulations of the entirety of the stellar interior, for which Blue Waters is ideally suited.

RESEARCH CHALLENGE

The teams are simulating brief but important events in the lives of stars that can greatly affect the heavier nuclei that the stars produce. We began by concentrating on hydrogen ingestion flashes, in which unburned hydrogen-rich fuel is brought into the convection zone above the helium-burning shell. Recently, we have turned our attention to massive stars, where in addition to H-ingestion flashes there is the possibility of the convection zones above different nuclear-burning shells actually merging. These events can have important consequences for the nucleosynthesis of heavy elements in these stars. For massive stars, such events can significantly affect the conditions just before the star explodes, and in this way, influence the injection of heavier elements from these stars into the surrounding interstellar medium.

METHODS & CODES

We are exploiting the Piecewise–Parabolic Method (PPM) gas dynamics method 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. This new code also solves nonlinear dynamical equations in which all the largest terms arising from the unperturbed, hydrostatic state of the star have been explicitly cancelled out. This makes the calculation accurate enough that the simulation is able to use 32-bit precision, which results in a doubling of the code's speed on Blue Waters. The new code also produces superior results on coarse grids, which increases its cost-effectiveness still further. In order to accurately describe the dynamics of fluid mixing at the convection zone boundary, we simulate many large-eddy overturning times in the convection zone above a nuclear-burning shell. The simulations are scaled to 2,176 nodes on grids of 768^3 cells and to 7,344 nodes for grids of $1,536^3$ cells. It can perform up to 48 timestep updates per second on Blue Waters. Thus, the millions of timesteps needed to simulate an ingestion event accurately are eminently practical on Blue Waters with the new code.

This year the team turned its attention 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 with the goal of alternating between 1D and 3D simulation in order to span the time necessary in leading up to a shell merger. The 3D simulations would keep models used in the 1D intervals that stitch one 3D run to the next validated as good descriptions of the full 3D results. We have been working up an attack on this shell-merger problem by first addressing ingestion of hydrogen-rich gas into the convective core of a massive star while it is still on the main sequence. Here, it is important to include the effect of rotation.

Early results from recent simulations on Blue Waters are shown in Figs. 1 and 2. We have described the techniques we use to achieve the extreme scalability of our codes in [1]. In [2], we describe the technique we developed with partial support from the Blue Waters PAID program to enable GPU acceleration. Our new code's exclusive use of 32-bit arithmetic is essential in enabling it to exploit the power of GPU accelerators by dramatically reducing the code's cache footprint.

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. Global convection modes play an important role in these situations, making simulation difficult and costly [3–5]. 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 [6,7].

WHY BLUE WATERS

We have carried out our simulations on Blue Waters because of its special ability to run at a sufficiently large scale so that our large computations can each be completed in less than one week [1]. 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 & DATA SETS

Woodward, P.R., F. Herwig, and T. Wetherbee, Simulating Stellar Hydrodynamics at Extreme Scale. *Computing in Science & Engineering*. In press (2018).

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Herwig, F., et al., Global Non-Spherical Oscillations in 3-D 4π Simulations of the H-Ingestion Flash. *Astrophys. J. Letters*, 792 (2014), p. L3.

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Ritter, C., et al., Convective-reactive nucleosynthesis of K, Sc, Cl, and p-process isotopes in O-C shell mergers. *Monthly Notices Royal Astron. Soc.*, 474 (2018), pp. L1–L6.

Herwig, F., et al., Cyberhubs: Virtual Research Environments for Astronomy. *Astrophys. J. Suppl.*, 236 (2018).

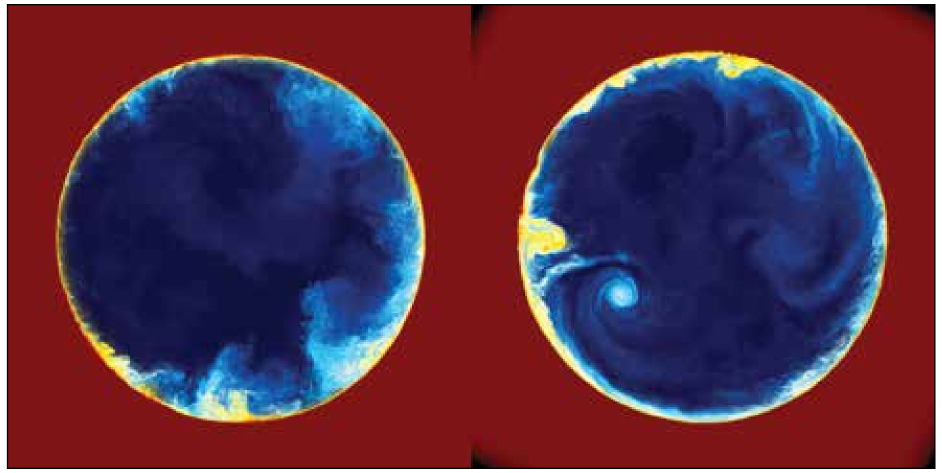

Figure 1: Snapshots of the distribution of ingested gas from above the convection zone generated by core hydrogen burning in a model 25 solar mass star. The star at the right rotates more rapidly. We look along the rotation axis at the far hemisphere in each case.

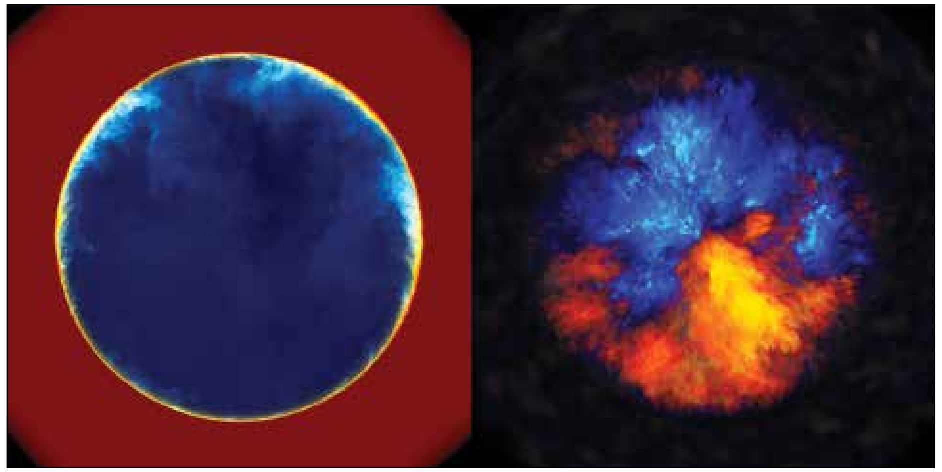

Figure 2: For the same model star as in Fig. 1, but with less rotation, we see a prominent dipole-like convection flow. Left, entrained gas, as in Fig. 1. Right, radial component of velocity (outward is red and yellow, inward is blue and white). Flow goes directly through the center of the star.