3-D SIMULATIONS OF I-PROCESS NUCLEOSYNTHESIS IN THE EARLY UNIVERSE

Allocation: PRAC/3.0 Mnh
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EXECUTIVE SUMMARY:

The scale and speed of Blue Waters enable 3D simulations of brief events in the evolution of stars that can have profound impacts upon their production of heavy elements. Hydrogen ingestion flash events have been identified as potential sites for the origin of anomalous abundance signatures in stars that formed in the early universe. We have simulated H-ingestion in a young white dwarf star, Sakurai's object, and in a very low-metallicity giant star formed in the early universe. Our results reveal an unstable, global oscillatory burning of the ingested hydrogen, which gives rise to quite different behavior than was anticipated from earlier 1D modeling of this phenomenon.

INTRODUCTION

The elements heavier than hydrogen and helium were manufactured within stars and later expelled into the interstellar gas to become incorporated in later generations of stars and planets. The late stages of evolution of the first generations of stars can be strongly affected by hydrogen ingestion events. These events occur, for example, when a convection zone above a helium burning shell in the asymptotic giant branch (AGB) stage of evolution of such stars reaches unprocessed hydrogen-helium gas above it. This gas is lighter than the helium and carbon mixture of such a helium shell flash convection zone and therefore is more buoyant. It resists being entrained into the gas of the convection zone yet can be dragged down as the result of convective boundary mixing. In order to understand the H-ingestion flashes, as well as the evolution of many other types of stars, it is critically important to be able to quantitatively simulate this convective boundary mixing.

At sufficient depth within the convection zone, the entrained hydrogen can react with the abundant 12C to form 13N, with a significant release of energy. The 13N decays, with a half-life of about 10 minutes to produce 13C and more energy. At the very high temperatures near the helium-burning shell, this 13C reacts with the remaining helium to produce oxygen and a free neutron at a very high rate. Neutrons produced in this way are then captured by trace concentrations of heavy elements in the gas to build an entire series of progressively heavier nuclei. This material can be expelled from the star along with its outer envelope as it forms a planetary nebula.

METHODS & RESULTS

Using 440,000 processor cores on Blue Waters, we simulated a very low metallicity AGB star of the early universe on a grid of 3.6 billion cells for more than 9 million time-steps. The simulated time is nearly two days in the life of the star, but in order to follow this star through the flash we increased the driving helium burning luminosity by a factor of 30 to more quickly traverse a slow ingestion period leading up to the flash.

Figure 1 shows six images of the local volume fraction of entrained hydrogen plus helium gas. We have cut away the front hemisphere of the star and look into the far hemisphere. We make the gas of the star's center transparent, whereas unprocessed hydrogen plus helium gas above the convection zone can be identified by its continuous red color. The gas that is otherwise visible consists of mixtures of the convection zone gas and the unprocessed hydrogen and helium mixture pulled from above the convection zone. The hydrogen concentration increases as the color changes from dark blue to aqua, then to white, yellow, and red.

The first image shows the star during the gradual buildup of entrained hydrogen in the upper part of the convection zone. Rising plumes of hotter, buoyant gas reaching the top of the convection zone spread horizontally along that upper surface. When they encounter other spreading flows, they are forced to turn downward, and it is here, along lanes separating convection cells, that buoyant hydrogen gas becomes entrained in the downward flow. These lanes appear dark blue because we see the low hydrogen concentrations in the gas first looking from the center of the star. Where the gas of the convection zone scrapes along the upper surface in a nearly horizontal flow, we see easily through the very thin layers of low hydrogen concentrations to the white, yellow, and red of higher hydrogen concentrations above.

In the second image, we see these higher concentrations mainly in cross-section around the edges of the spherical convection zone top. A layer of gas enriched with hydrogen has accumulated at the top of the convection zone. At the lower left, we see high hydrogen concentrations in red and yellow, where a wave traveling around the top surface of the convection zone is peeling off a slice of the hydrogen-helium gas above. This is the characteristic sign of a global oscillation of shell hydrogen ingestion, which we call a GOSH. It is a result of unstable hydrogen burning that we have discovered in this work by adopting a global, 3D description of the flow in contrast to previous models in 1D approximation. These waves rushing back and forth can raise the hydrogen ingestion rate by two orders of magnitude or more, which is expected to have significant impact on heavy-element production.

In the image at the middle left, the layer of buoyant, hydrogen-rich gas near the top of the convection zone impedes convective motions, and further hydrogen ingestion proceeds more slowly. But heat continues to be deposited into the convection zone from helium burning and from hydrogen burning at the base of this upper layer, and buoyant plumes punch into the upper layer of hydrogen-rich gas (middle right image) and bring that gas down to the high temperatures, where it burns violently. The resulting bursts of huge, localized energy release cause violent updrafts that set off a more powerful GOSH, seen in the bottom two images.

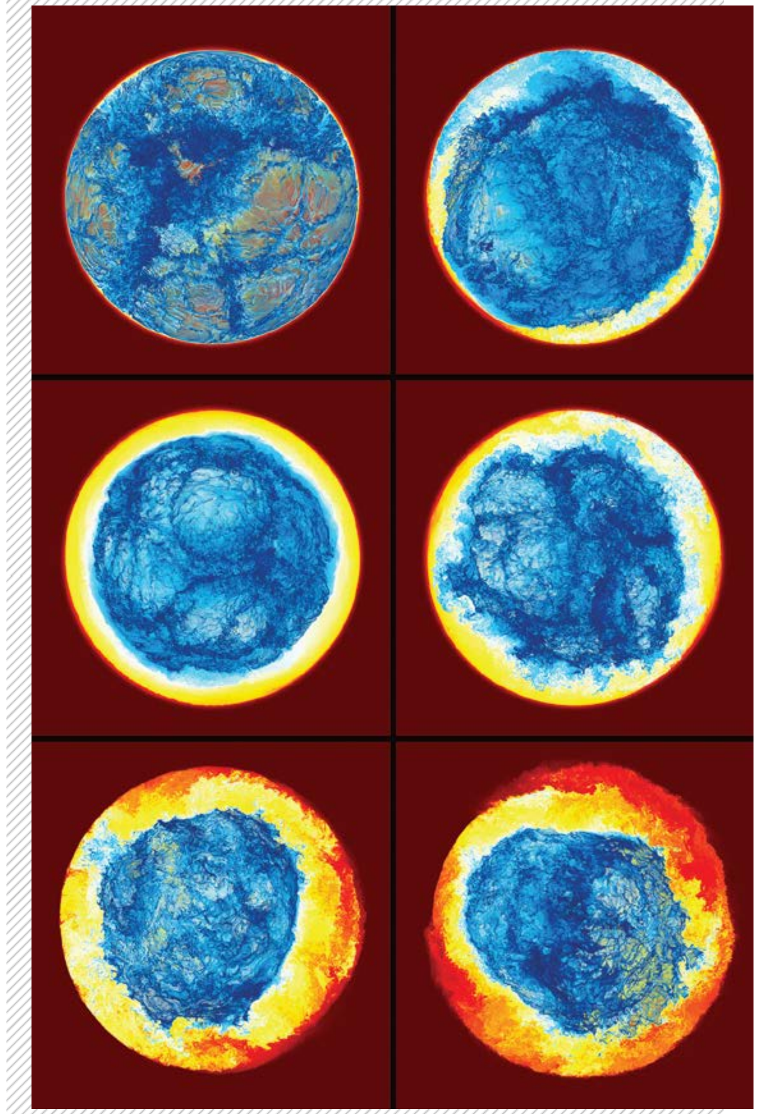

FIGURE 1: Entrainment of hydrogen-rich gas into the helium shell flash convection zone of a very low metallicity star and the subsequent development of the Global Oscillation of Shell Hydrogen ingestion (GOSH).

WHY BLUE WATERS

The sustained petaflops capability of Blue Waters makes it possible to perform 3D simulations that allow us to explore and understand phases of stellar evolution that are long in duration compared to a stellar explosion but short compared to those behaviors that are well approximated by 1D codes.

PUBLICATIONS

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THREE-DIMENSIONAL CORE-COLLAPSE SUPERNOVA SIMULATIONS

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EXECUTIVE SUMMARY:

Core-collapse supernovae are the most common type and occur when the iron core of a massive star collapses to a neutron star. Releasing its gravitational binding energy as neutrinos, the protoneutron star (PNS) for a few seconds outshines the rest of the observable universe. Capturing a small fraction of this energy is thought to power the explosion of at least the most frequent supernovae, though detailed calculations proving this paradigm are still lacking. We conduct three-dimensional radiation/hydrodynamic simulations of core-collapse supernovae with the goal of determining the mechanism of explosion, using the newly developed and tested code Fornax, incorporating state-of-the-art microphysics and methodologies.

INTRODUCTION

Viewed as a nuclear physics laboratory, core collapse supernovae produce the highest densities of matter and energy in the modern universe. They thus probe the nuclear and particle physics of matter at super-nuclear density, high temperature, and at extremes of isospin. They are also responsible for creating most of the elements in nature, many of which are produced as radioactive precursors, both neutron-rich (r- process) and neutron-poor (explosive nucleosynthesis). The neutrino signal they emit carries information about the nuclear equation of state, and the strength of their explosion is sensitive to how both the neutrinos and ultra-dense matter are treated. Supernovae, thus, probe the same sort of physics as the Facility for Rare Isotope Beams, the Argonne Tandem Linac Accelerator System, and low-energy runs at Brookhaven's Relativistic Heavy Ion Collider, the Facility for Antiproton and Ion Research in Damstadt, Germany, CERN's SPS Heavy Ion and Neutrino Experiment, and Russia's Nuclotron-based Ion Collider Facility. Our project employs our new state-of-the-art radiation/hydrodynamics code Fornax to simulate the physics of core collapse and explosion in three spatial dimensions. This effort supports NSF's experimental nuclear physics program by exploring nucleosynthesis in astrophysical explosions, the properties of the neutrino, and the equation of state and phases of dense nuclear matter. A solution to the core-collapse supernova problem would benefit ongoing efforts of observers and instrument designers in the United States and around the world engaged in projects to determine the origin of the elements, measure gravitational waves (LIGO), and interpret laboratory nuclear reaction rate measurements in light of stellar nucleosynthesis.

METHODS & RESULTS

Fornax is a new code for multidimensional, self-gravitating, radiation hydrodynamics that is second-order accurate in space and time and was designed from scratch with the core-collapse supernova problem in mind. The code solves the equations of compressible hydrodynamics with an arbitrary equation of state, coupled to the multigroup two-moment equations for neutrino transport and the Poisson equation for gravity. The equations are solved on a fixed Eulerian grid, enhanced by a mechanism for static mesh derefinement in the inner zones. All of the these transport related terms are treated explicitly in time and are updated with the same time-step as the hydrodynamics. After core bounce, explicit time integration is not only simpler and generally more accurate, it is also faster than globally coupled time-implicit transport solves that are typically employed in radiation hydrodynamics methods. The latter allows us to avoid angular Courant limits at the center, while maintaining accuracy and enabling us to employ the useful spherical coordinate system natural for the supernova problem. We have spent much of the first phase of our Blue Waters effort developing, testing, and running Fornax. Our project has received a modest extension, and we hope to have 3D simulation results to report in 2016.

WHY BLUE WATERS

It is not possible to explore this central problem in nuclear astrophysics without supercomputer resources such as Blue Waters. Its Cray architecture comports very nicely with our code architecture, and the large number of cores available enables the exploitation of our code's efficient parallelism. On a small, Beowulf-like cluster, we estimate that one calculation would take a few decades to perform, while requiring only one month on Blue Waters, using one-quarter of the machine.