FIGURE 1: Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times for the Pulsar-like case. Arrows indicate plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system after an incipient jet is launched.

to be the initial endorsement of the NS with a dipole B field that extends into the NS exterior, as in a pulsar magnetosphere. By contrast, if the initial B field is confined to the interior of the NS, no jet is observed [3]. These results prompt the query of whether NSNS mergers produce jets in the same way as BHNS systems, or does of the mechanism requires an initial BH.

Previous ideal GRMHD simulations by Rezzolla et al. suggest that NSNS mergers may launch a relativistic jet [4], while those by Kiuchi et al., which focus on different initial configurations, show otherwise [5]. Both of these studies have considered only scenarios where the B-field is initially confined to the interior of the two NSs.

Using our latest adaptive-mesh refinement GRMHD code we performed simulations of equal mass NSNS binaries initially on a quasicircular orbit that undergo merger [6]. The initial stars are irrotational, n=1 polytropes and are magnetized. We explore two types of B field geometries: one where each star is endowed with a dipolar B field extending from the interior into the exterior (Fig. 1, upper left), as in a pulsar, and the other where the dipolar field is initially confined to the interior of the two NSs.

Unlikely the BHNS case, the B field does not grow following BH formation: the existence of the HMNS phase instead allows the B field to build to saturation levels prior to BH formation. We do observe a gradual growth in the ratio B²/2ρ above the BH pole due to the emptying of the funnel as matter accretes onto the BH. At ~66 ms, following the merger of the two NSs, incipient jets are launched even when the initial B field is confined to the interior of the stars (Fig. 1, lower right). The duration of the accretion and the lifetime of the jet is ~0.1 seconds, which is consistent with short-duration short gamma ray bursts. The luminosity is 1051 erg/s, also consistent with observed short gamma ray bursts values. Our simulations provide theoretical corroboration that mergers of NSNS systems can indeed launch jets and be the central engines that power short gamma ray bursts.

WHY BLUE WATERS

By adding OpenMP support to our message interface passing (MPI)-based code, scalability on multicores machines has improved greatly. With the Blue Waters next-generation interconnect and processors, our hybrid OpenMP/MPI code exhibits greater scalability and performance than on any other supercomputer we have used. Recently, we were able to build our code with the Blue Waters Intel compilers. This resulted in a 30% boost of our code’s performance, making Blue Waters unique for tackling the astrophysical problems we want to address.

Blue Waters is also used by our undergraduate research team to make visualizations (e.g., Fig. 1) and movies of our simulations with the VisIt software.

PUBLICATIONS


THE MOST MASSIVE GALAXIES AND BLACK HOLES AT THE COSMIC DAWN OF THE UNIVERSE

EXECUTIVE SUMMARY

Our team has led the development of cosmological codes adapted to petascale supercomputers and used Blue Waters to understand how the first massive black holes and galaxies were formed, from the smallest to the rarest and most luminous. Using nearly one trillion particles, we have carried out the BlueTides simulation on Blue Waters. BlueTides can answer questions in cosmology which require simulations of the entire visible universe at high mass and spatial resolution. We can directly predict what should be seen in future observations that will probe the cosmic dawn of the universe and the formation of the first galaxies and black holes.

INTRODUCTION

Survey astronomy has enabled the study of galaxy and large-scale structure formation at low redshifts to mature into a precise science. Current galaxy surveys at high redshift, however, have covered very small volumes of space in the early universe during the epoch of formation of the first galaxies and quasars. The search for the earliest objects in the universe is extremely challenging. From the observational point of view, the field will be transformed by the next generation telescopes (JWST, WFIRST, etc.). In the coming decade, a new generation of astronomical instruments will observe the universe at the time of the formation of the first stars and quasars, opening up the “last frontier” in astronomy and cosmology.
Numerical simulations of galaxy formation have been limited by the volume at which they can evolve. From the simulation-theoretical perspective, large-scale uniform volume hydrodynamic simulations of the high redshift universe are a problem ideally suited to modern petascale facilities like Blue Waters. It is now feasible to run memory-limited observational selection algorithms (SourceExtractor) on the simulated sky maps and build catalogs of millions of galaxies. The high resolution of BlueTides made it possible to produce detailed images of individual galaxies and uncover a striking and unexpected population of large Milky Way-sized disk galaxies (Fig. 2) present when the universe was 5% of its present age. Both of these achievements will be of great benefit to the burgeoning frontier fields that will utilize JWST and WFIRST.

**WHY BLUE WATERS**

A complete simulation of the universe at the epochs we are studying requires a small enough particle mass to model the dwarf galaxies which significantly contribute to the summed ionizing photon output of all sources. It also calls for an enormous volume: 1 cubic Gigaparsec (3x10^19 cubic light years) equivalent to a high particle density and the second largest particle volume.

**METHODS & RESULTS**

**Massive disk galaxies in the early universe**

Our current run of BlueTides allowed us to apply observational selection algorithms (SourceExtractor) to the simulated sky maps and build catalogs of expected quasars that will be discovered shortly.
EXECUTIVE SUMMARY

Explosions of massive stars (core-collapse supernovae; CCSNe) have a significant impact on the development of galaxies and their heavy element content. We compute 3D simulations of CCSNe that include the complex range of CCSN physics, across the range of input conditions representing the history of massive stars in the universe to obtain the variety of outcomes seen in nature. Our computations account for the appropriate nuclear processes needed to generate and eject heavy elements that are needed to form planets. We have discovered a previously unseen nuclear burning behavior that can only be observed through the completeness of our simulations and the included nuclear physics.

CORE-COLLAPSE SUPERNOVAE THROUGH COSMIC TIME

Allocation: NSF PRAC/8.94 Med
PI: Eric J. Lentz
Co-PIs: Stephen W. Bruenn, W. Raphael Hix, O. E. Bronson Messer, and Anthony Mezzacappa
Co-Thurates: J. Austin Harris

University of Tennessee
Florida Atlantic University
Oak Ridge National Laboratory
Lawrence Berkeley National Laboratory

METHODS & RESULTS

To compute CCSN models in the necessary 3D, we have developed Chimera, a program that accounts for neutrino transport and opacities, nuclear equations of state and reaction networks, composable fluid dynamics, and self-gravity [1, 2]. This project addresses the wide range of pre-supernova stellar configurations from the range of initial masses and the build-up of heavy elements (mostly from previous CCSNe) through cosmic history by sampling in both dimensions. From these models we will address the nature of the CCSN mechanism and the production of elements in the explosions.

In the low-mass, primordial composition simulation in our grid, we have identified a previously unseen burning mode in stellar collapse. During collapse, compression of the silicon shell intensifies the burning of the remaining oxygen at the bottom of the layer until it triggers a silicon flash. The silicon flash burns much of the silicon shell to iron-peak elements and some of the overlying oxygen-neon shell to silicon. The deposited energy alters the collapse dynamics and helps intensify the explosion driven by neutrino heating from the collapsed iron core interior. Silicon flashes have been observed in pre-supernova stellar evolution models for similar progenitors [3], but were not seen in previous work with the same progenitor [4] as nuclear burning was not adequately included.

WHY BLUE WATERS

Computing stellar explosions in 3D requires large and long computations. Blue Waters provides the capacity needed to accommodate our simulation requirements.

NEXT GENERATION WORK

More powerful and capable machines will permit improvements in the computationally expensive portions of CCSN simulations (neutrino transport, nuclear networks, resolution). This will help to better realize the nature of the explosions and increased simulation counts to better account for the variety of inputs and outcomes.

INTRODUCTION

Massive stars (mass greater than eight solar masses) are relatively rare; yet they play a significant role in the evolution of galaxies, particularly through their explosive finales as CCSNe. Energy from CCSNe triggers new star formation and elements synthesized in massive stars and CCSNe are the ingredients for terrestrial planets in those star systems. The conversion of gravitational potential energy from the collapse of the stellar core into an explosion of the stellar envelope is a complex physical process. This physical process combines gravitation, nuclear physics, neutrino physics (neutrinos transport the needed energy to drive the explosion from the collapsed core), and turbulent fluid dynamics with a rich phenomenology.

PUBLICATIONS AND DATA SETS


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