Results from our simulations indicate that we can reproduce the high-redshift galaxy luminosity functions observed by Hubble. The simulations also predicted the numbers of galaxies fainter than those observed so far. Depending on how much UV radiation can escape from these low-mass galaxies, these galaxies can produce enough stellar radiation to completely reionize the intergalactic medium. This reionization occurs on a timescale that is consistent with observations of absorption in high redshift quasars and polarization of the cosmic microwave background.

We also made significant improvements in the algorithms used for the treatment of Black Hole formation, dynamics, and feedback. With this new treatment, we can reproduce observed star formation and black hole accretion histories, star formation histories and supermassive black hole masses in Milky Way-sized galaxies over the age of the universe.

WHY BLUE WATERS

We used the same mass and resolution requirements from our previous resolution tests to reliably model galaxy form and structure. Therefore, the size of the simulations we performed are set by the sub-volume of the universe we wish to model. HST surveys of high-redshift, star-forming galaxies cover a volume comparable to a cube 25 Mpc. This volume not only allowed us to make direct comparisons with HST surveys but also to enhance their value by providing a better understanding as to how these galaxies evolve to the present.

Proper treatment of black hole dynamics also requires high dark matter mass resolution. This treatment is needed so that the sinking of black holes to the centers of galaxies is not interrupted by two-body scattering on the dark matter. Combining these two resolution requirements with the complete simulation requires an order of magnitude more computationally intensive than what we could previously use. Therefore, a sustained petascale facility like Blue Waters was necessary.

NEXT GENERATION WORK

Nevertheless, this simulation was still a compromise. For example, if we wish to understand how high-redshift galaxies influence surrounding intergalactic gas, a much larger volume of gas will be needed in our simulations. Intergalactic gas is studied from absorption observations of background quasars using the HST Cosmic Origins Spectrograph. Statistical samples of this gas require a volume of order 60 Mpc; over an order of magnitude larger than our current simulation. Simulations made with samples of this magnitude is the only way we will be able to understand the extent to which star formation, supernovae, and active galactic nuclei in individual galaxies influence the surrounding gas, and to conduct a proper census of the majority of the baryonic matter in the universe. The next generation of Track-1 computational resources will be required to run simulations using higher volumes of intergalactic gas.

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FIGURE 2: Distribution of gas (left) and stars (right) in a group of galaxies at z = 0.25. Stars are colored by their formation time such that young stars are white. Comparing left and right images, one can find a number of gas-free galaxies with older stellar populations.

BINARY NEUTRON STARS MERGERS: A JET ENGINE FOR SHORT GAMMA-RAY BURSTS

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EXECUTIVE SUMMARY

The LIGO-Virgo Collaborations recently reported the first direct detection of a gravitational-wave (GW) signal produced by the inspiral and coalescence of a binary black hole (BHBH) system. This breakthrough marks the beginning of the era of gravitational-wave astrophysics. GWs are expected to be generated not only by BHBH binaries but also by neutron star-neutron star (NSNS) and black hole-neutron star (BHNS) binaries. Merging NSNSs and BHNSs are not only important sources of GWs but also the two most popular candidates to produce relativistic jets and serve as the engines which power short-hard gamma-ray bursts (sGRBs). Simultaneous observation of GWs and gamma rays from these systems is the holy grail of multimessenger astronomy. We have performed ideal magnetohydrodynamic simulations of NSNS systems in full general relativity and have shown unambiguously that they can indeed launch incipient jets even when the initial B field is confined to the interior of the stars.

INTRODUCTION

A century after the General Relativity (GR) was published, the LIGO-VIRGO collaboration reported, for the first time, the direct detection of the GWs (event GW150914) [1]. This detection provided a spectacular confirmation of GR theory as the fundamental theory of gravitation and confirmed the existence of BHs and BHBHs. Most importantly, this breakthrough opens a new window to our universe, as GWs can provide us with information that cannot be obtained from the typical electromagnetic spectrum. This includes the observation of BHBH and measurement of their properties, the study of the early universe before the recombination era, as well as the nature of matter above nuclear density. Also, GW signals are expected to be generated not only by BH binaries but also from NSNSs and BHNSs, among other compact objects. Many of these sources are likely to also generate electromagnetic (EM) radiation counterparts to the GWs. Detecting both GW and EM radiation from the same cosmic source will constitute a major advance in multimessenger astronomy.

GRBs were first discovered in 1967, and theorists have been working to explain them ever since. The mergers of a NS with a companion NS or BH are the two most popular candidate progenitors of short gamma ray bursts, those with a duration less than two seconds. These systems are thus excellent candidates for multimessenger detection. To verify the binary-short gamma ray bursts association and properly interpret the GW and EM signals we will receive, we need to model these systems and simulate their evolution in full general relativity with magnetohydrodynamics (GRMHD). Our work to date has focused on studying the merger of magnetized BHNS and NSNS systems.

METHODS & RESULTS

GRMHD numerical simulations require the solution of the GR equations to determine the gravitational field, the relativistic MHD equations to determine the flow of matter, and Maxwell's equations to determine the electromagnetic fields. Together the equations constitute a large system of highly nonlinear, multidimensional, partial differential equations in space and time.

Recently, we demonstrated that mergers of magnetized BHNS systems can launch jets and be the engines that power short gamma ray bursts [2]. The key ingredient for generating a jet was found

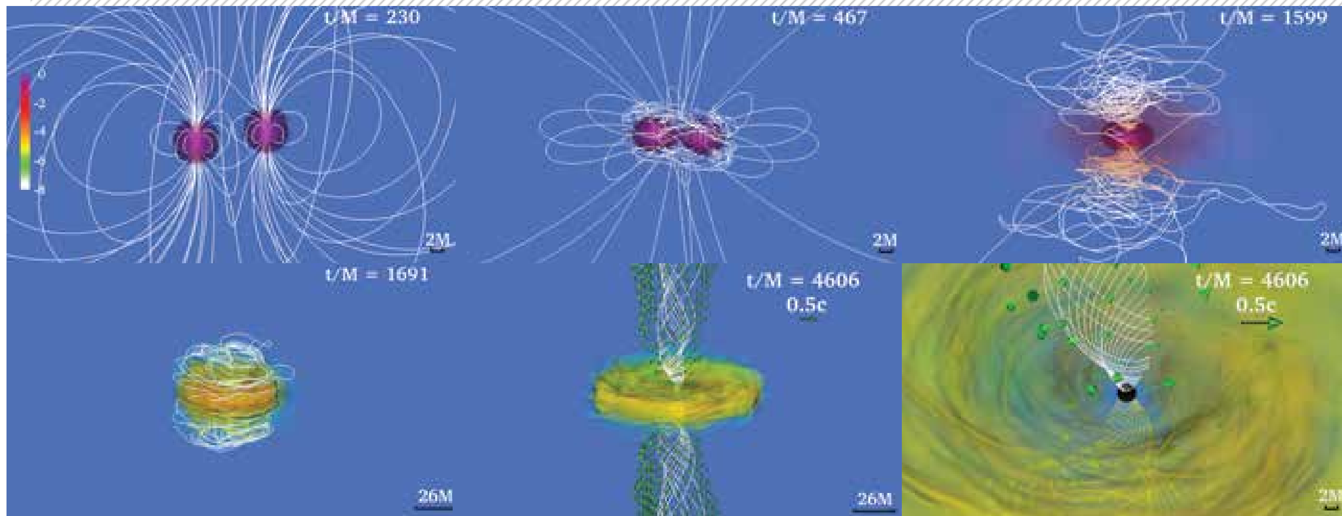

FIGURE 1: Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times for the Pulsar-like case. Arrows indicate plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system after an incipient jet is launched.

to be the initial endowment 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 Rezolla 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. In both cases, the adopted B fields are dynamically unimportant initially. To ensure reliable evolution of the exterior field and properly mimic the conditions that likely characterize the exterior magnetosphere, in the pulsar-like case, we initially imposed a low-density atmosphere such that the NS exterior was described by a constant plasma parameter, defined as the ratio of the gas pressure to the magnetic pressure. We then continued the evolution through the merger of the two NS and subsequent formation of a hypermassive NS (Fig. 1, upper center and right) that undergoes delayed collapse to a BH immersed in a magnetized accretion disk (Fig. 1, lower left and center).

Unlike in 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 multi-core 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.

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

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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.