MAGNETOROTATIONAL COLLAPSE OF SUPERMASSIVE STARS: BLACK HOLE FORMATION, GRAVITATIONAL WAVES, AND JETS

Allocation: Illinois/990 Knh
PI: Stuart L. Shapiro[1]
Co-PIs: Vasileios Paschalidis[2], Milton Ruiz[1], and Antonios Tsokaros[1]
Collaborator: Lunan Sun[1]

[1]University of Illinois at Urbana-Champaign
[2]Princeton University

EXECUTIVE SUMMARY

We perform magnetohydrodynamic (MHD) simulations in full general relativity (GR) of the collapse of radially unstable, uniformly rotating, massive stars to black holes (BHs). The stars spin at the mass-shedding limit, account for magnetic fields and obey a polytropic $\Gamma = 4/3$ equation of state (EOS). The calculations lift the restriction of axisymmetry imposed in previous simulations. Our simulations model the direct collapse of supermassive stars (SMSs) to supermassive BHs (SMBHs), with masses larger than $10^4\ M_\odot$, at high cosmological redshifts z, which may explain the appearance of SMBHs and quasars by $z \sim 7$. They also crudely model the collapse of massive Population III stars to massive BHs, which could power some of the long gamma-ray bursts observed by FERMI and SWIFT at $z \sim 6\text{-}8$. We analyze the properties of the electromagnetic and gravitational wave signatures of these events and discuss the detectability of such multimessenger sources.

RESEARCH CHALLENGE

SMBHs with masses between $10^6\ M_\odot$ and $10^9\ M_\odot$ reside at the center of most galaxies, including our own galaxy [1]. It is not clear however what are their growth mechanisms since in the early universe (high redshift) there is comparatively a small amount of matter to feed them and less than a billion years for them to consume it. It has been suggested that first generation stars (Population III stars) could collapse and form seed BHs, which later could grow through accretion to become SMBHs [2,3]. An alternative scenario explaining the origin of SMBHs is provided by the direct collapse of stars with masses $\geq 10^4\ M_\odot$. These so-called SMSs could form in metal–, dust–, and H_2–poor halos, where fragmentation and formation of smaller stars could be suppressed [4]. We study the evolution of radially unstable, uniformly rotating magnetized SMSs modeled by polytropes with a radiation-dominated ($\Gamma = 4/3$) equation of state that undergo collapse to BHs with masses larger than $10^4\ M_\odot$ in full GR. These simulations also crudely model the collapse of massive Population III stars to massive BHs, which could power some of the long gamma-ray bursts observed by the FERMI and the SWIFT satellites at redshift $z \sim 6\text{-}8$. These calculations lift the restriction of axisymmetry imposed in previous studies and extend the initial magnetic field to full-space geometry [5].

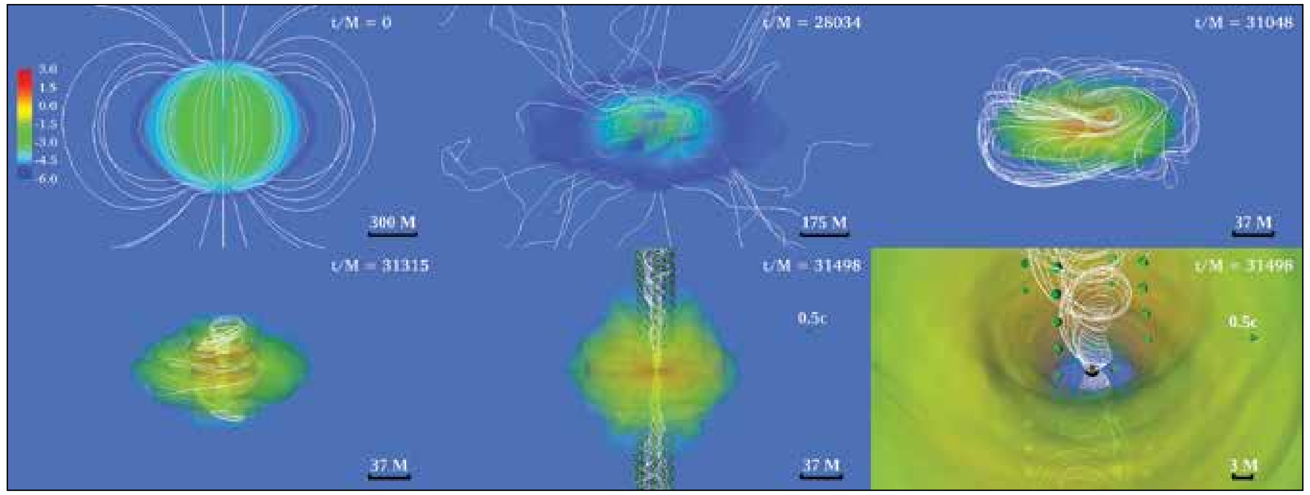

Figure 1: Volume rendering of the rest-mass density normalized to its initial maximum value (log scale) at selected times. Arrows show plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system during and after an incipient jet is launched.

METHODS & CODES

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

We solve the above equations through our completely independent "Illinois GRMHD code", which has been built over many years on the Cactus infrastructure and uses the Carpet code for adaptive mesh refinement, but employs our own algorithms and coding (see e.g. [6]). This code utilizes state-of-the-art high resolution shock capturing methods to evolve scenarios involving either vacuum or matter spacetimes, with or without magnetic fields. It utilizes the Baumgarte-Shapiro-Shibata-Nakamura (BSSN) formulation of the Einstein field equations with puncture gauge conditions. It solves the magnetic induction equation by introducing a vector potential and employs a generalized Lorentz gauge condition to reduce the spurious appearance of strong B-fields on refinement level boundaries [6].

Our undergraduate research team also creates visualizations (e.g., Fig. 1) and movies of our simulations with the VisIT software on Blue Waters.

RESULTS & IMPACT

Using our latest adaptive-mesh refinement GRMHD code we performed simulations of massive stars that undergo collapse [5]. We consider a purely hydrodynamic case, and two magnetized cases, one seeded with a poloidal magnetic field only in the stellar interior and the other extended from the stellar interior to the exterior (Fig. 1, upper left). In both cases, the adopted magnetic fields are dynamically unimportant initially. To ensure reliable evolution of the exterior field, we initially impose a low-density atmosphere such that the stellar exterior is described by a constant plasma parameter, defined as the ratio of the gas pressure to the magnetic pressure. To accelerate the collapse, the pressure is initially depleted by 1% in all our cases. We then evolve the stars through the collapse and subsequent BH formation immersed in a magnetized accretion disk (Fig. 1, top right and bottom panels).

We find that, in terms of the BH mass, its spin and torus mass, the results from our hydrodynamic simulations are consistent with previous semi-analytic estimates and axisymmetric simulations in GR reported in [7-8]. We also find that the magnetic field do not affect these global quantities.

In the magnetized cases, following BH formation we observe the formation of magnetically dominated regions above the BH poles where the magnetic field lines have been wound into a collimated helical funnel, within which the plasma flows outwards. This collimated outflow is mildly relativistic, and constitutes an incipient jet. Our analysis suggest that the Blandford-Znajek effect is likely operating in our simulations and could be the process powering these jets. The magnetization in the funnel reaches values ≥ 200, and since for steady-state, axisymmetric jets the magnetization approximately equals the jet terminal Lorenz factor, the jets found in our simulations may reach Lorentz factors of 200, and hence, explain gamma-ray burst (GRB) phenomena. The accretion torus lifetime is $\Delta t \sim 10^5(1 + z)(M/10^6\ M_\odot)$s. Thus, collapsing SMSs with masses $\sim 10^3\ M_\odot$ - $10^4\ M_\odot$ at $z \sim 10\text{-}20$ are candidates for ultra-long GRBs, while collapsing Population III stars at $z \sim 5\text{-}8$ are candidates for long GRBs. We estimated that for observation times of $\sim 10^4$ s, FERMI and SWIFT could detect such ultra-long GRB events from these stars [9].

WHY BLUE WATERS

By adding OpenMP support to our MPI-based code, scalability on multi-core machines has improved greatly. With the Blue Waters 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 Intel compilers on Blue Waters, which resulted in a significant boost of our code's performance by about 30%, making Blue Waters unique for tackling the astrophysical problems we want to address.

PUBLICATIONS AND DATA SETS

Sun, L., V. Paschalidis, M. Ruiz, and S. Shapiro, Magnetorotational Collapse of Supermassive Stars: Black Hole Formation, Gravitational Waves and Jets. ArXiv:1704.04502.

Ruiz, M., R. Lang, V. Paschalidis, and S. Shapiro, Binary neutron star mergers: a jet engine for short gamma-ray burst. *Astrophys. J.*, 824 (2016), pp. L6–L11.

Shapiro, S.L., Black holes, disks and jets following binary mergers and stellar collapse: The narrow range of EM luminosities and accretion rates. *Phys. Rev. D*, 95 (2017), pp. 101303–124071.

Tsokaros, A., et al., Gravitational wave content and stability of uniformly, rotating, triaxial neutron stars in general relativity. *Phys. Rev. D*, 95 (2017), pp. 124057–124071.