Numerical GRMHD Simulations of Self-Gravitating Collapsing Stars

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ABSTRACT

Gamma-ray bursts are one of the most energetic phenomena in the Universe. Long gamma-ray bursts are associated with the collapse of massive stars. We present, for the first time, three-dimensional GRMHD simulations of collapsars incorporating both the gravity of the central black hole and the self-gravity of the massive stellar envelope. We compare models with self-gravity (SG) and without self-gravity (NSG) under identical initial conditions in order to investigate the specific effects of self-gravity on the system. We discuss the time evolution of black hole mass, spin, and accretion energy rate, as well as jet properties, accretion flow, and disk fragmentation.

COLLAPSAR MODEL

The collapsar model is the most widely accepted explanation for the origin of long gamma-ray bursts. According to this model, the collapse of a rapidly rotating massive star leads to a sequence of processes resulting in long GRBs (Woosley 1993). The progenitor must possess sufficient angular momentum to form an accretion disk in the equatorial plane. In the collapsar scenario, this plane is coaligned with the equatorial plane of the newly born rotating black hole. The jet is launched along the rotation axis and lasts as long as the accretion disk exists, although other conditions also influence its duration.

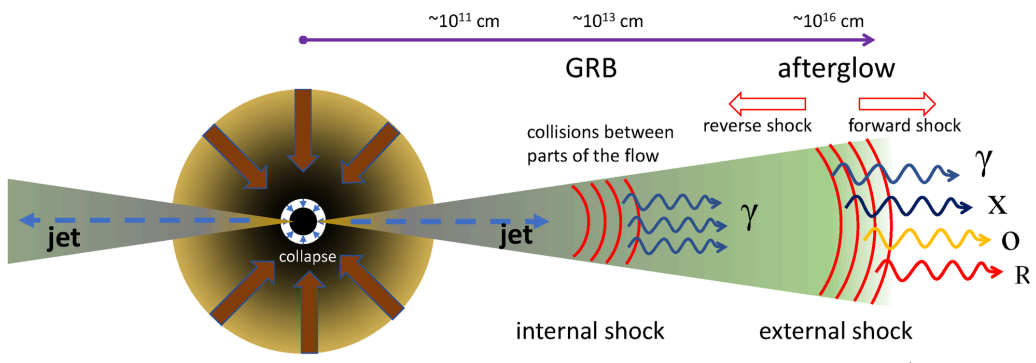

Figure 1: Schematic view of the long gamma-ray bursts emission mechanism from the collapsar (Dado et al. 2022).

METHODS

We performed numerical simulations using the code HARM (High Accuracy Relativistic Magnetohydrodynamics), which is a numerical scheme and code for solving magnetohydrodynamics equations in the framework of general relativity (Gammie et al. 2003; Noble et al. 2006). HARM solves the following three equations (the continuity equation, the conservation of energy and momentum, and the induction equation governing the evolution of the magnetic field):

$$\nabla_\mu(\rho u^\mu) = 0, \quad \nabla_\mu(T^\mu_\nu) = 0, \quad \nabla_\mu(u^\mu b^\nu - u^\nu b^\mu) = 0.$$

Additionally, in our implementation of HARM, we dynamically evolve the spin and mass of the central black hole by calculating the fluxes of energy and angular momentum through the event horizon. The implementation of self-gravity from the stellar envelope is based on calculations of the energy and angular momentum enclosed in the volume between a given point and the event horizon. The appropriate perturbation terms are added to the Kerr-Schild metric. We parametrized our collapsar models using seven free parameters: the ratio of gas pressure to magnetic pressure at the inner point (β), the initial mass of the black hole (M_{BH}), the initial mass of the stellar envelope (M_{star}), the initial spin of the black hole (a_0), the parameter (S) scaling the angular momentum relative to that at the ISCO, the type of magnetic field configuration, and the amplitude of the perturbation in the internal energy. Two models have the identical initial conditions. The resolution is set to 384×192×128.

Model	β	M_{BH} ($M_\odot$)	M_{star} ($M_\odot$)	a_0	S	Magnetic Field	Perturbation (%)	Jet
Model-1-SG	1	3	25	0.8	2	vertical	5	yes
Model-1-NSG	1	3	25	0.8	2	vertical	5	yes

ACCRETION FLOW AND JET LAUNCHING

Relativistic astrophysical jets are highly collimated outflows. The main mechanism responsible for launching Poynting jets is the Blandford–Znajek process (Blandford & Znajek 1977). In Poynting jets, the majority of the energy is initially stored in the electromagnetic field. This energy is then dissipated, converted into the kinetic energy of particles, and eventually partially emitted as highly energetic radiation. To measure the energetics of jets, we use the Lorentz factor estimated at infinity. This parameter is defined under the assumption that all forms of energy are converted at infinity to the baryon bulk kinetic energy (Vlahakis & Königl 2003; Sapountzis & Janiuk 2019). The Lorentz factor at infinity is given by the equation:

$$\mu = \Gamma_\infty = -\frac{T^r_t}{\rho u^r}.$$

To measure the opening angle of jets, we use magnetization σ, defined as the ratio of magnetic energy density to rest-mass energy density:

$$\sigma = \frac{b^2}{\rho}, \quad b^2 = b^\mu b_\mu.$$

Our method for measuring the opening angle is based on identifying the region where $\sigma > 1$.

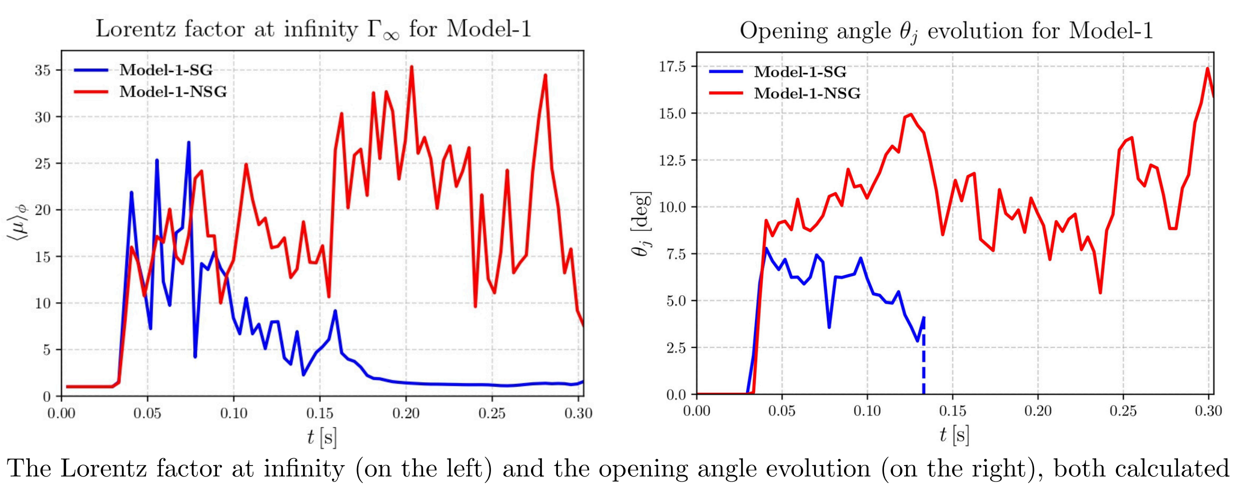

Figure 2: The Lorentz factor at infinity (on the left) and the opening angle evolution (on the right), both calculated at 150 r_g. We observe that in the model with self-gravity, the Lorentz factor at infinity does not achieve as high values as in the model without self-gravity. Moreover, we observe gradual jet quenching in the model with self-gravity. The opening angle in the model without self-gravity is significantly greater than in the model with self-gravity. Note that self-gravity doesn't affect jet formation time.

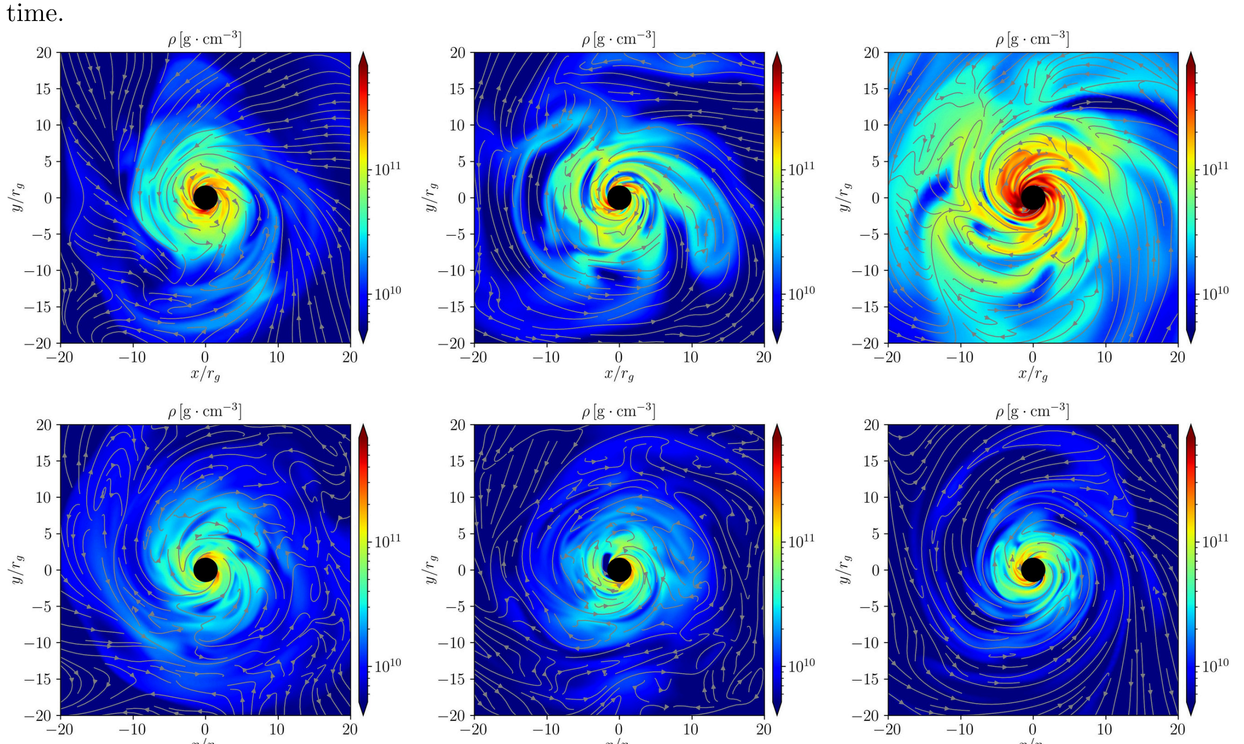

Figure 3: Equatorial slices of 3D simulations, showing maps of the mass density, overlaid with magnetic field lines. All quantities are evaluated on the equatorial plane for Model-1-SG (top row) and Model-1-NSG (bottom row). Columns from left to right correspond to times t = 0.0369 s, 0.0739 s, and 0.1108 s, respectively. We note an increasing amount of mass accumulating in the vicinity of the black hole in the model with self-gravity. In the model without self-gravity, the amount of matter near the black hole event horizon remains almost constant over time. The accumulation of mass is responsible for the jet quenching visible in Figure 2. Our implementation of self-gravity provides additional pressure strong enough to overcome the magnetic barrier, leading to the start of accretion visible in Figure 4. Furthermore, the additional inward pressure on the jet funnel in the model with self-gravity makes the jet opening angle narrower.

JET PROPERTIES AND BLACK HOLE EVOLUTION

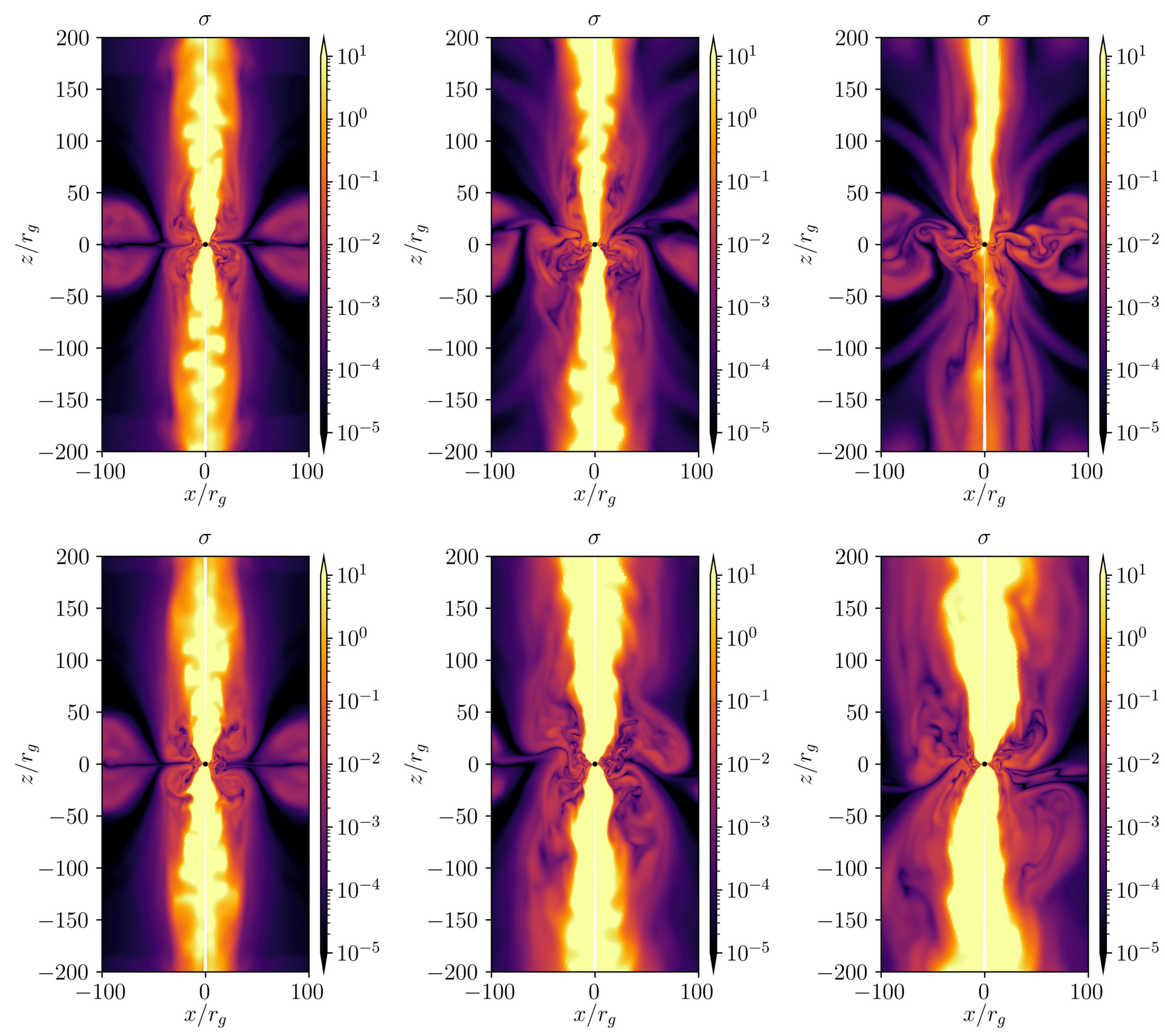

Figure 4: Equatorial slices of 3D simulations, showing maps of magnetization σ, evaluated in the poloidal plane aligned with the rotation axis for Model-1-SG (top row) and Model-1-NSG (bottom row). Columns from left to right correspond to times t = 0.0369 s, 0.0739 s, and 0.1108 s, respectively. Due to the accumulation of matter, we observe a gradual decay of jet magnetization in the model with self-gravity, leading to jet quenching. Similar to Figure 2, we observe that the opening angle is narrower in the model with self-gravity.

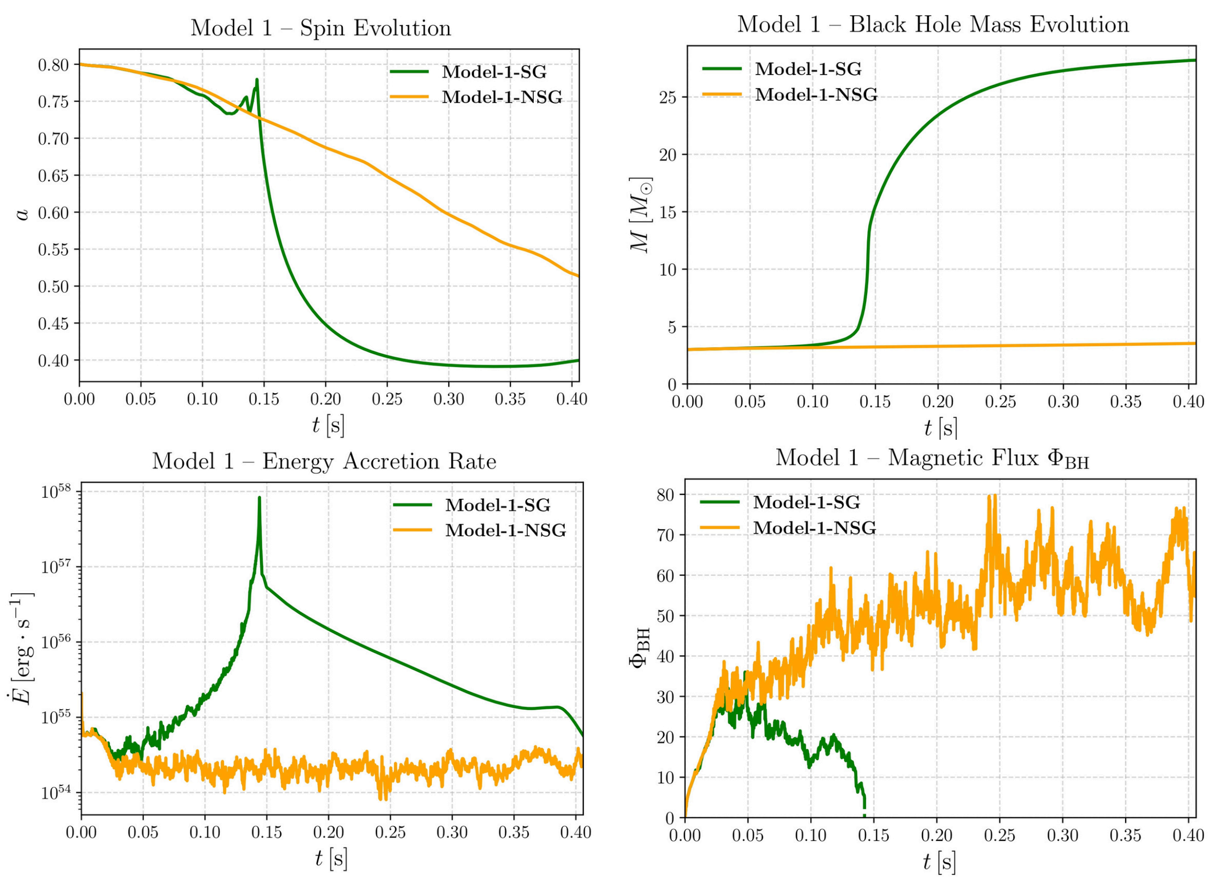

Figure 5: Evolution of the black hole spin, mass, accretion energy rate, and the dimensionless magnetic flux. We observe that in the model without self-gravity, the black hole mass remains almost constant throughout the evolution. The decrease in spin indicates the extraction of rotational energy from the central black hole via the Blandford–Znajek process (Blandford & Znajek 1977). Regarding the accretion rate, we note that Model-1-NSG exhibits large variability because the system reaches the Magnetically Arrested Disk (MAD) state (Tchekhovskoy et al. 2011), while in the model with self-gravity, the stable MAD state is not achieved.

DISK FRAGMENTATION

To measure the effects of disk fragmentation, we investigate amplifying and damping modes (m) using the Fourier transform. We observe that self-gravity shifts the distribution of modes toward higher orders. The higher-order modes are visible as small clumps of matter in the disk. Another property of the self-gravity system is that the inner-region density is significantly higher, which is shown in Figure 5.

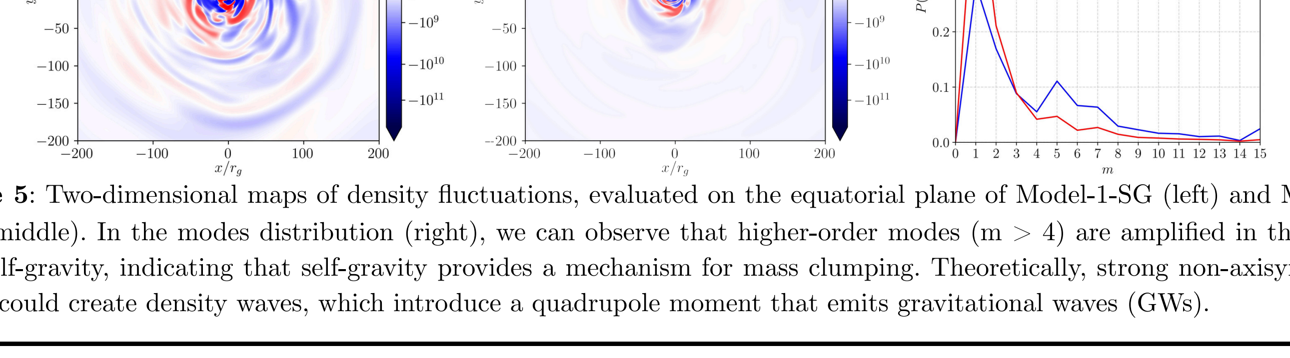

Figure 5: Two-dimensional maps of density fluctuations, evaluated on the equatorial plane of Model-1-SG (left) and Model-1-NSG (middle). In the modes distribution (right), we can observe that higher-order modes ($m > 4$) are amplified in the model with self-gravity, indicating that self-gravity provides a mechanism for mass clumping. Theoretically, strong non-axisymmetric modes could create density waves, which introduce a quadrupole moment that emits gravitational waves (GWs).

CONCLUSIONS

We show that in our three-dimensional GRMHD models of collapsars, the timescale and energetics of jet emission strongly depend on whether self-gravity is included. We observe that the jet opening angle is significantly smaller when self-gravity is present. The jet in the model without self-gravity is more energetic and remains active for a longer time. Self-gravity adds inward pressure on the magnetically arrested disk, pushing it toward the black hole and, as a result, suppressing jet emission. Additionally, self-gravity amplifies the power of higher-order azimuthal modes in the Fourier spectrum and shifts the distribution toward them.

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