Black Hole - Neutron Star Collisions: A Mechanism for Short Gamma-Ray Burst Production

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Introduction

Progenitors of Short Gamma-Ray Bursts (SGRB) are yet unknown. One of the many proposed models is the encounter and collision between black holes and compact stars such as neutron stars within dense stellar clusters.

A recent Newtonian study supports this SGRB mechanism.[1] With the motivation that accuracy will increase when General Relativity (GR) is considered, the study presented here will perform GR simulations using parameters similar to the Newtonian study, compare results, and assess the validity of the proposed SGRB mechanism.

- **Short Gamma-Rays Bursts** (SGRB)– Flash of high energy electromagnetic waves which last an average of one second
- **Neutron Star** – Star of nuclear density created after a massive star supernova explosion
- **General Relativity** (GR) – A theory of gravitation, space, and time for extremely dense objects
- **Newtonian Gravitation** – A limiting case of GR for moderately dense objects

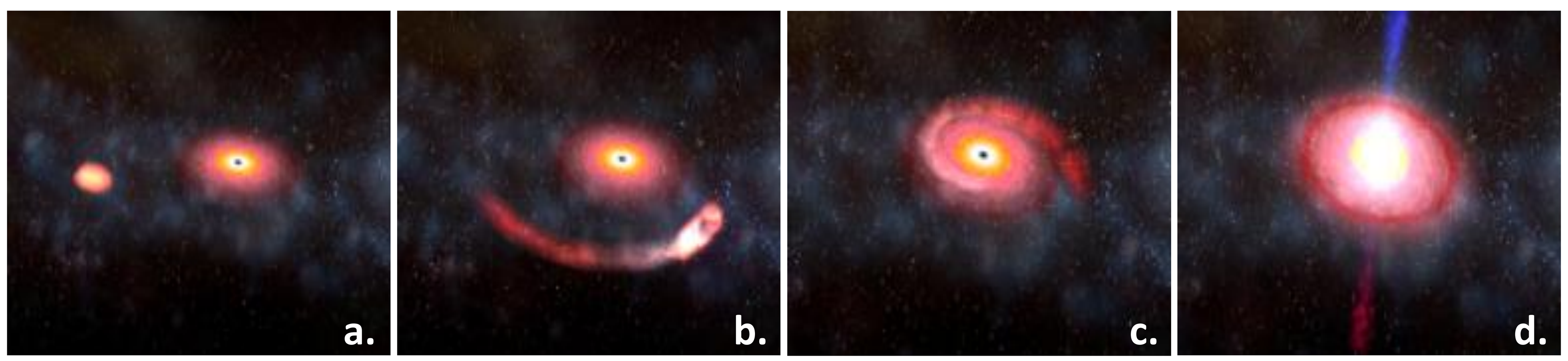


FIG. 1.– An artist's rendition of an encounter between a black hole and a neutron star. Notice the neutron star forms a disk and a tail around the black hole in image (c). These formations are crucial to the Short Gamma-Ray Burst mechanism. A Gamma-Ray Burst jet is illustrated in image (d). Pictures courtesy of NASA. *http://www.nasa.gov/mission_pages/swift/bursts/short_burst_oct5.html*

Methods and Procedure

Black Hole – Neutron Star collisions were modeled on high-performance computers. Initial parameters necessary for collision were estimated and used as input for simulations. Certain quantities which may indicate the validity of this mechanism such as the mass of the neutron star, gravitational and thermal radiation, and time duration of the collision are computed throughout a simulation.

Simulation Tools

Einstein Toolkit	• Relativistic astrophysics software • Open - source
Cactus[2]	• Scientific software framework • Open - source
Queen Bee	• LONI core supercomputer • 50.7 Tflop peak performance • 669 node cluster
LONI	• Louisiana Optical Network Initiative • Network of supercomputers in Louisiana/Mississippi Region

Initial Configuration

Neutron Star	
Mass (M☉)	1.4
Velocity (km/s)	9.6×10^4
Position (km) [x,y]	[-76, 0]

Black Hole	
Mass (M☉)	4.51
Velocity (km/s)	3.0×10^4
Position (km) [x,y]	[24, 0]

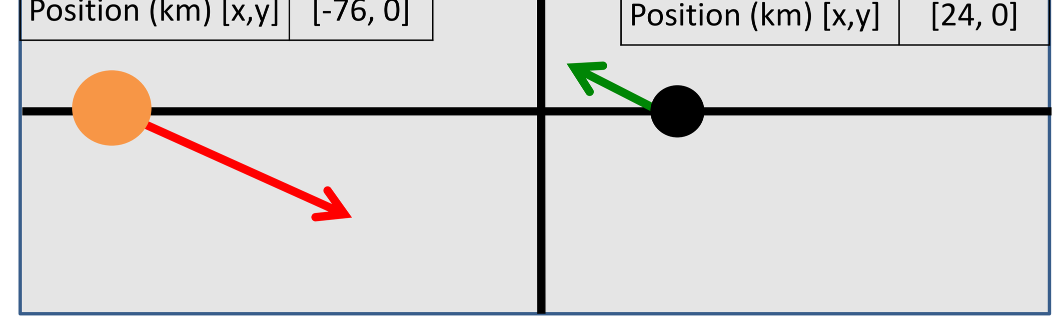


FIG. 2.– Simulation input configuration. Velocities were estimated by assuming parabolic orbits and distance of closest approach (periastron), 20.1 km.

Results

The latest collision model is represented below (see Figure 3). The current state of the simulation indicates a potential SGRB production; however, to be certain of the occurrence of a SGRB, the simulation must be followed for a longer timescale (1 to 2 seconds).

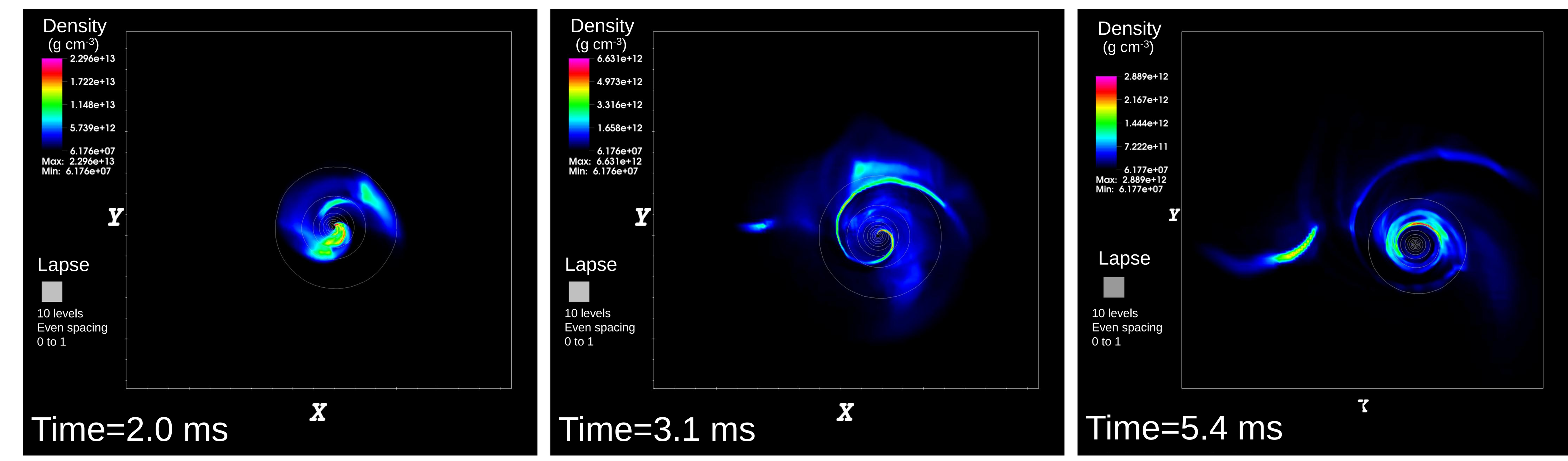


FIG. 3. –Disruption of a neutron star by tidal (gravitational) forces of a black hole. Two-dimensional slice through the orbital plane. The center of the black hole is located at the center of contours.

Collision Traits

NS disruption	yes
Disk formation	yes
Disk mass	0.127 M☉
Estimated disk lifetime	~ 1 s

TABLE. 2.– These quantities are indicative of a Short Gamma-Ray Burst. For example, the disk mass and lifetime comply with theoretical requirements.

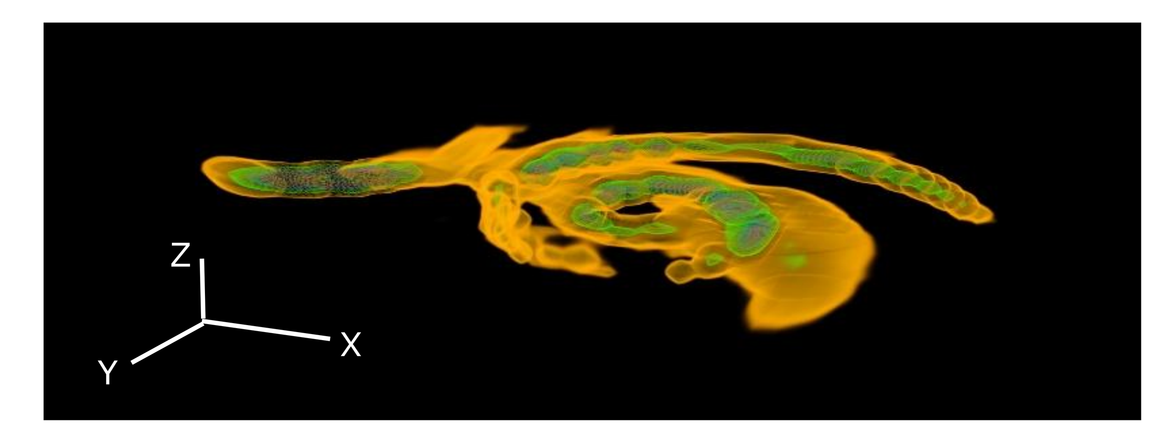
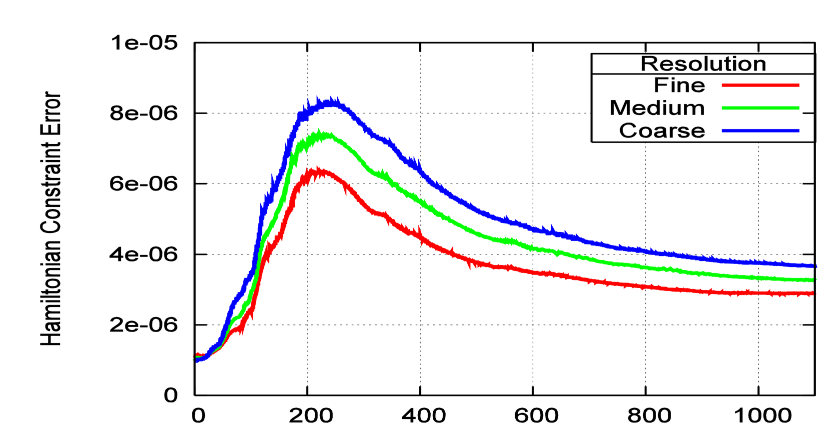


FIG. 4.– 3D visualization of disk formation at Time = 5.4 ms created using Vish software[3], courtesy of Edwin Mathews.



Error Analysis

Simulations must maintain, among other physical restrictions, a Hamiltonian Constraint error H close to the theoretical value zero as a condition of accuracy. Figure 5 provides a qualitative implication of convergence of the numerical solutions.

FIG. 5.– Evolution of H for three different resolutions. Notice the finer resolutions have smaller error as is expected.

Future Work

- Consider a longer time evolution of the latest simulation to observe complete accretion of the disk.
- Explore larger sets of parameters such as various neutron star and black hole masses.
- Improve the data initialization method currently employed by Einstein Toolkit to increase model accuracy.
- Perform a rigorous comparison with Newtonian models.
- Analyze neutron star oscillations and thermodynamics to build correlations with changes in system energy.

Acknowledgments

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References

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[2] Cactus Code, http://cactuscode.org/
[3] Vish Visualization Environment, *http://vish.origo.ethz.ch/*