Simulations of binary black hole mergers

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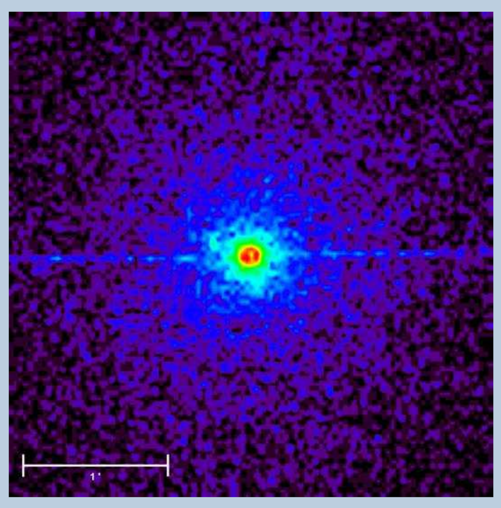
Motivation

We envisage a model for an extremely long duration gamma ray burst, with possible double jets and/or jets redirected, and leaving an orphan afterglow, while accompanied by a gravitational wave signal. Such GRB would be resulting from the collapse of a massive rotating star in a close binary system with a companion black hole.

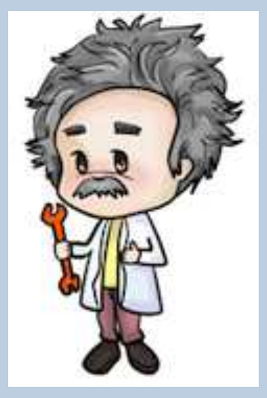


Candidate for such scenario: Cygnus X-3, the X-ray binary system composed of the Wolf-Rayet star, which will undergo core-collapse supernova, and its companion BH.

Physics

The first stage, core-collapse, is computed semi-analytically. The numerical simulation covers the second stage of the event, the evolution of binary BH system, when the separation of its components becomes so small, that the phases of inspiral, merger, and ring-down are tracked. The full set of Einstein equations is solved numerically to model the geometry of spacetime. We consider two black holes in quasi circular orbits with mass ratios varying from 1 to 3. The more massive black hole carries also spin perpendicular to the orbital plane, and the second component is spinless. In the first approximation, we neglect the influence of the surrounding matter (circum binary disc) on the BBH merger and simulate dynamics of the vacuum solution.

Numerics



We use `Einstein Toolkit` computational package, *http://www.einsteintoolkit.org*.
The initial data: given masses, momenta and spins for each BH. The initial separation of components is the same for each run and is equal to $6M$ (M is approximately equal to *ADM* mass of the whole system). The constraints for the initial Cauchy data for BBH are solved numerically.
The evolution: 3+1 split of Einstein equations, solving the Cauchy initial value problem using Baumgarte-Shapiro-Shibata-Nakamura (BSSN) method.
Grid: Cartesian $48\times48\times48M$, resolution: $dx = 1.6M$. 7 levels of the adaptive mesh refinement by factor 2 in two regions around singularities. The regions of refined grid follow the positions of BH's.
Analysis: The apparent horizons are localized around the components of the BH system and around final merged black hole after it forms. The proper integrals over the isolated horizons are calculated to extract the values of mass and spin of the merged black hole.

Two example scenarios

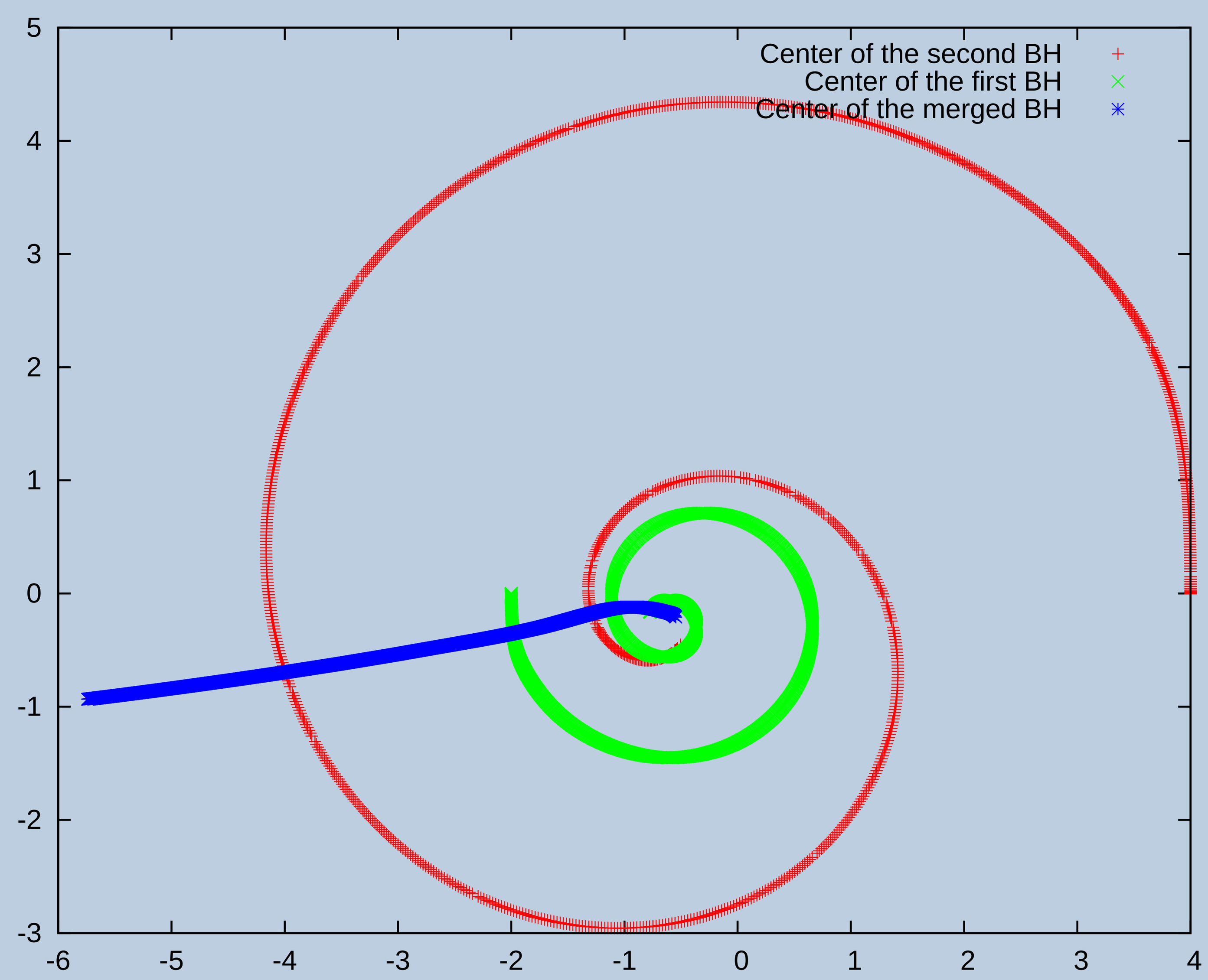
The input parameters and results for two example runs represent two possible scenarios, that might occur during the 1st stage (core-collapse): A, the homologous accretion and B, the torus accretion with mass loss.
In A, $M_1 \sim 9M_\odot$, $M_1/M_2 \sim 3$ and $M_3 \leq M_{env}$.
In B, $M_1 \sim 4M_\odot$, $M_1/M_2 \sim 1$ and $M_3 \geq M_{env}$.

	Initial state										Final state	
	Control parameters					Computed ADM values					ADM	
run	m_1	m_2	p_1	p_2	a_1	M_1	M_2	$\frac{M_1}{M_2}$	M	$\frac{a_1}{M_1^2}$	M_3	$\frac{a_3}{M_3^2}$
A	0.63	0.32	-0.17	0.17	0.9	1.05	0.35	3.0	1.39	0.81	1.34	0.76
B	0.54	0.45	-0.14	0.14	0.28	0.6	0.45	1.4	1.03	0.79	0.98	0.78

Parameters in the Table are evaluated in geometric units, used in numerical simulations. Since the vacuum solutions of Einstein equations are scalable they can be easily rescaled to fit the astrophysical constrains given above.

Gravitational recoil

The picture shows the trajectories of the component BHs during the two last orbits of BH binary (red and green), and the trajectory of the final BH (blue).



The effect of gravitational recoil of the final BH is clearly visible. Since the gravitational radiation caries momentum, we estimate the kick velocity of the final BH. We obtained the values of recoil speed to be approximately 200 km/s (scenario A) and 300 km/s (scenario B). In future work we plan to analyze the interaction of the recoiled BH traveling through the surrounding circum binary disk and its possible influence on the GW emission.

References & Acknowledgments

[1] A. Janiuk, S. Charzyński, M. Bejger, *Astronomy & Astrophysics*, A25, **560**, and refs. therein.

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