Simulations of Black Hole-Neutron Star Mergers

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Background

Abstract

Black hole-neutron star (BHNS) mergers are exciting events to model, as they are a source of gravitational waves (GWs), like those discovered for the first time by Advanced LIGO earlier this year. These mergers are also the source of gamma-ray bursts and radioactively powered transients. We present here an outline of our entire simulation process. We display results of general relativistic-hydrodynamic simulations using the Spectral Einstein Code (SpEC), and our post-processing analysis.

Motivation

- We need to better understand/predict the light curves of transients, because they follow the GW signal [1]
- Neutron-rich material is ejected from BHNS and NS mergers
- within seconds, ejecta will form into heavy elements via r-process nucleosynthesis
- Heavy nuclei are unstable, and decay into lighter elements while heating ejecta and powering supernova (SN)-like transient
- Called "r-process" SNe (kilonovae) light curves; much dimmer, short-lived; evidence of one discovered before in [2]

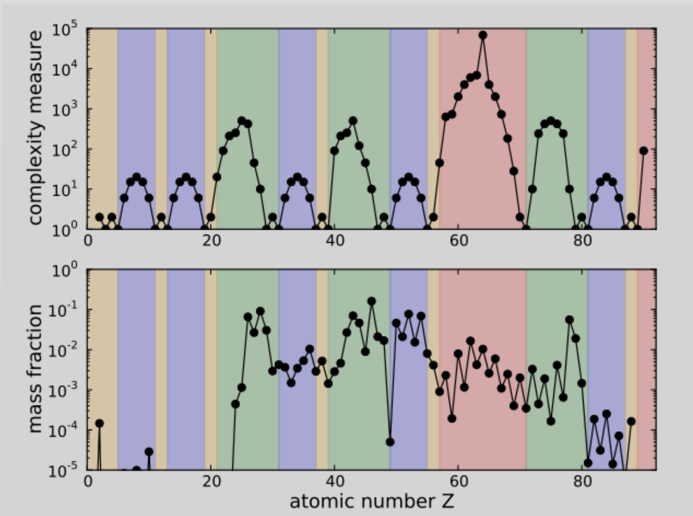

Figure 1: The above diagram describes the ejecta of a NS merger. In the top panel, we show the number of possible energy configurations for each atomic number. In the bottom panel, we show the mass fraction of various ions by atomic mass, in the ejecta. Unlike in SNe, r-process yields elements heavier than Fe (Taken from [3])

- In [3], emission spectrum of ejecta was assumed to consist of ions with greater complexity, i.e. ions heavier than iron, since this would yield more possible transitions
- Lanthanides dominate total opacity (see Fig. 1), resulting in opacities 1 order of magnitude greater than expected
- Transient emission should thus be dimmer and longer in duration than previously thought

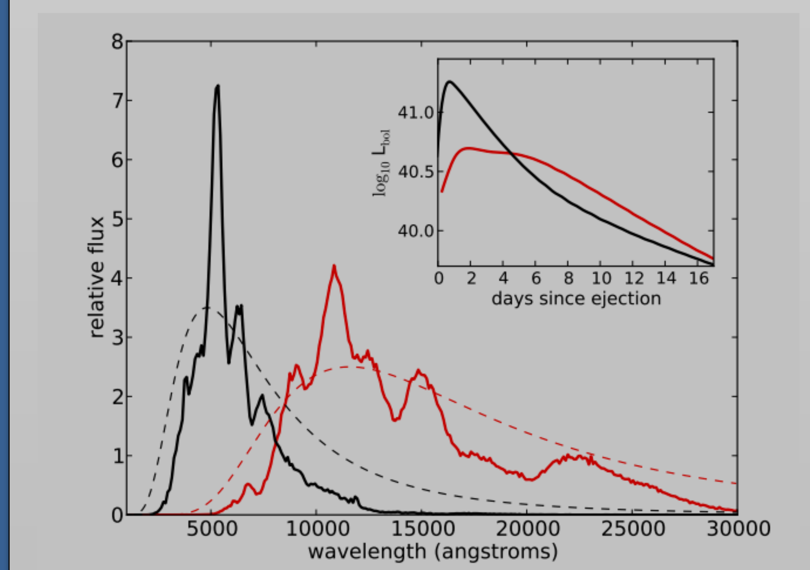

Figure 2: Above are the spectra and light curves of ejecta with two different set ups. The black curve represents ejecta consisting of Fe (as exist in SNe), while the red represents ejecta comprising of lanthanide elements. It is clear that rSN emissions are cooler and last longer (Taken from [3])

Methods

Spectral Einstein Code

- Simulations were run remotely on 80-90 cores on a supercomputer cluster managed by ComputeCanada, using the Spectral Einstein Code developed by the SxS (Simulating Extreme Spacetime, https://www.black-holes.org/) collaboration
- Disk and tidal tail is evolved for ~10 ms before inputting data into post-processing code
- These simulations are novel because they include a treatment for neutrinos ([4]), and are precessing ([5])
- We ran simulations with parameters described in table to the right

Summary of Initial Configurations

Name of System	Mass of BH (M)	Spin Magnitude of BH	Spin Inclination (degrees)
M7_S8	7	0.8	0
M7_S7	7	0.7	60
M5_S7	5	0.7	60
M5_S9	5	0.9	60

Post-Processing Methods

- Tidal tail is further evolved in Newtonian potential (with corrected velocities), for ~1 second, using 4th order RK integrator
- Fallback rate: rate at which marginally bound material in the tidal tail falls back to the disk
- Densities were approximated throughout evolution by proximity of particles to nearest neighbors

Results

We present one of the results of the SpEC simulation below, approximately ~10ms into the merger event.

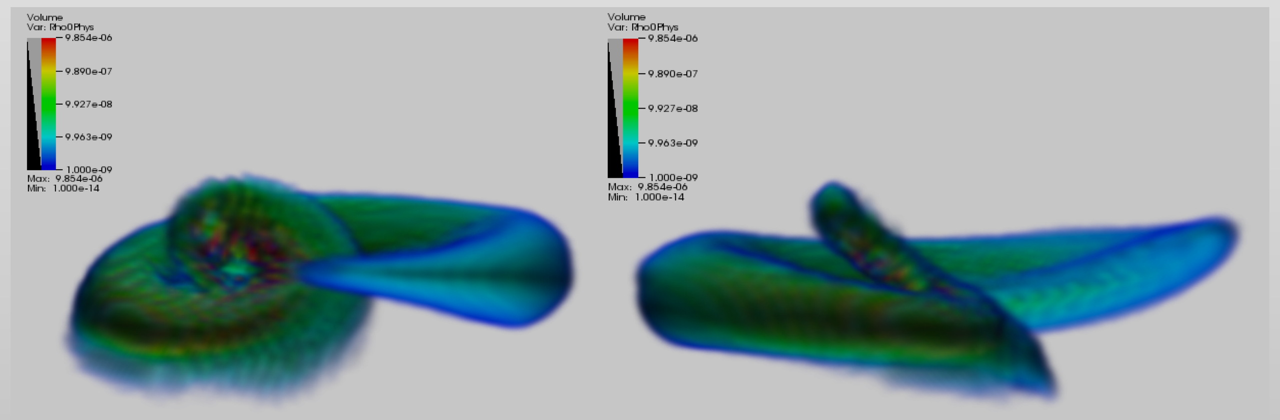

Figure 3: M5_S9 from two different perspectives. Precession of the forming disk is evident – matter clearly lies in two distinct planes.

Results

Fate of Bound and unbound matter

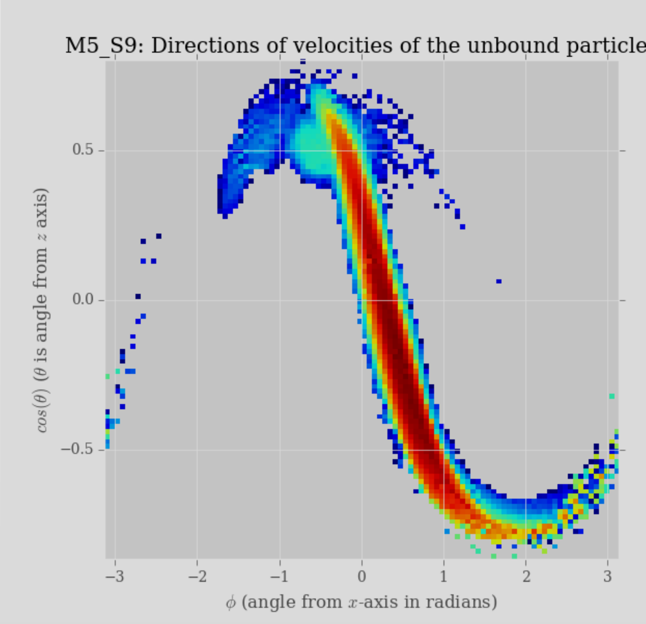

Figure 4: Distribution of ejecta. Most matter is contained in one, twisted plane due to precession.

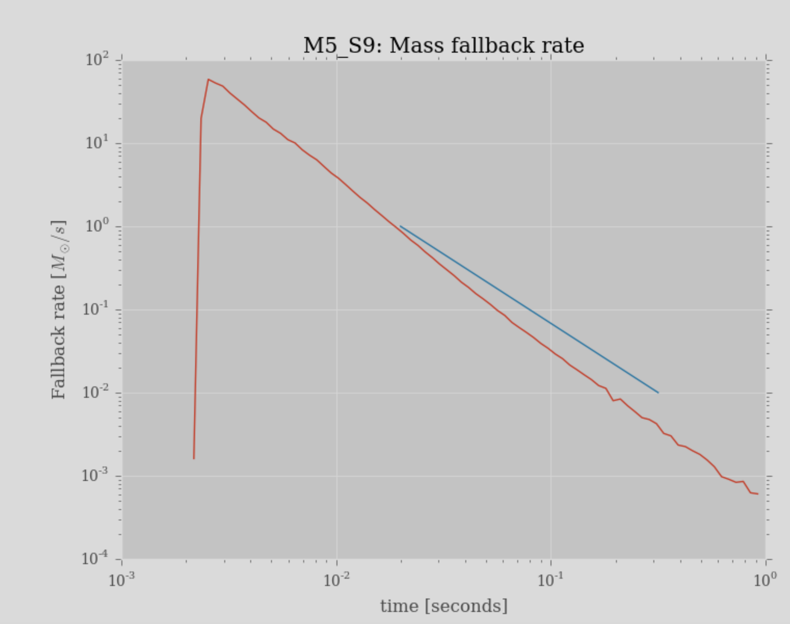

Figure 5: Rate at which bound matter reaches its periapse in orbit around BH; blue line represents expected fallback rate (which should follow a curve proportional to $t^{-5/3}$) while red line is data from the simulation.

Density Evolution

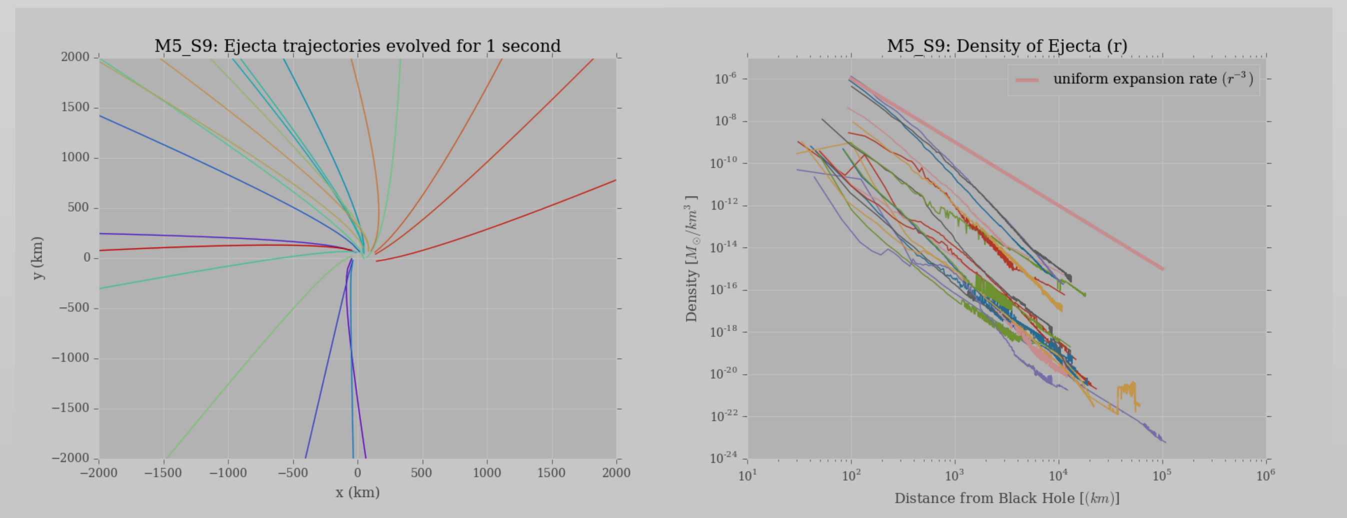

Figure 6-7: On the left, we have trajectories of unbound particles projected onto the xy-plane. On the right, are densities as a function of distance of the same particles as they are ejected from the BH.

Density Evolution

- Can use with initial temperature of ejecta to determine mass fractions of heavy elements formed
- Can use ejecta distributions for radiation transport analysis, as in [3]

Conclusions & Future Directions

- Fallback rates correspond fairly well to the theoretical $t^{-5/3}$ decay
- There are clear differences in the distribution of ejecta for precessing and non-precessing systems: ejecta for non-precessing systems, as expected, lay in the equatorial plane, while the ejecta for M5_S9 and M5_S7 lay in a twisted plane, due to procession

For the future…

1) Add source due to heating from radioactive decay
2) Ejecta outflow plots can be used to improve modeling of radioactively powered transients

Acknowledgements

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References

[1] J. Abadie et al. 2010. Classical and Quantum Gravity, Volume 27, Issue 17, id. 173001.
[2] N. R. Tanvir et al. 2013. Nature, Volume 500, Issue 7464, pp. 547-549 .
[3] Daniel Kasen, N.R. Badnell, & Jennifer Barnes. 2013. The Astrophysical Journal, Volume 774, Issue 1, article id. 25, 13 pp.
[4] M. Brett Deaton, Matthew Duez et al. 2013. The Astrophysical Journal, Volume 776, Issue 1, article id. 47, 15
[5] Francois Foucart, Brett Deaton et al. 2013. Physical Review D, vol. 87, Issue 8, id. 084006.