Usage Report for Fiscal Year 2018

Project Title:

Long-Term Evolution of Neutron-Star Merger Remnants and Calculation of Their Gamma-Ray Signals

Name:

○ **Oliver Just (1), Hirotaka Ito (1), Shigehiro Nagataki (1), Stephane Goriely (2)**

(1) Astrophysical Big Bang Laboratory, RIKEN Cluster for Pioneering Research

(2) University of Brussels

1. Background and purpose of the project, relationship of the project with other projects

Neutron stars born in a binary emit gravitational waves, which extract energy and angular momentum from the system and ultimately cause both objects to fall into each other and coalesce. Such neutron star mergers have for a very long time been speculated to be the progenitors of short gamma-ray bursts (sGRBs), and they are believed to produce substantial amounts of neutron-rich outflows, which would make them significant sources of the heaviest elements in the Universe, such as Gold and Uranium. The recent, spectacular first direct observation of a binary neutron star merger, the so-called event GW170817, sparked lots of attention. It not only finally proves the existence of neutron-star mergers, it also lends strong support to the idea of neutron-star mergers being the progenitors of sGRBs and significant sources of heavy elements.

However, after GW170817 many questions still remain open, such as: What is the mass, velocity, geometrical shape, and composition of all outflow components that have been observed in gamma-rays as well as optical, radio and X-ray emission coincidently with GW170817? In order to obtain the optimal scientific gain from (existing and upcoming) observations of neutron-star mergers, it is therefore crucially important to improve theoretical models until they are sophisticated enough to provide a convincing explanation for all observed data.

In our current project, G18035, we use newly constructed models of the remnant of a neutron-star merger (consisting of a black-hole accretion-disk system) to follow the propagation of a highly relativistic jet through the cloud of material that has been ejected before the launching of the jet. By doing so we want to investigate a) whether these models can explain the prompt gamma-ray signal of GW170817 and b) whether the jet has an impact on the nucleosynthesis yields of the expanding ejecta. So far, these are the first simulations that can follow the black-hole disk system together with the jet and the expanding ejecta. Also, these simulations are currently the only ones, based on which a sophisticated Monte-Carlo radiation transport scheme is employed to extract the prompt gamma-ray signal.

This project is a direct continuation of the Quick Use project Q18380. Q18380 ran from April 2018 until October 2018, while this project (G18035) started in October 2018 and will end in March 2019. During Q18380 we mainly developed and tested the jet models, which are now (i.e. within G18035) being investigated in larger sets and higher resolution.

2. Specific usage status of the system and calculation method

For the hydrodynamical simulations we employ the code AENUS-ALCAR, which solves the special relativistic hydrodynamics equations together with the M1 approximation of neutrino transport on a fixed, Eulerian mesh using Riemann-solver based finite-volume methods. The code (of which O. Just is a main co-developer) was extensively tested and applied in a number of published studies.

The simulations are supposed to describe the evolution of black-hole accretion disks formed after neutron-star mergers. We start the simulations using approximate solutions for the accretion disk and the surrounding ejecta. In order to follow the neutron-content of the disk and ultimately be able to analyze the nucleosynthesis yields in the ejected material, we need to follow the transport of electron neutrinos and antineutrinos additionally to the hydrodynamic evolution of the gas. The jet is launched from the central region as a result of heating in the polar regions above and below the black hole, which in a parametrized manner mimics the "Blandford-Znajek" mechanism. Since a self-consistent description of the Blandford-Znajek mechanism would demand a much more expensive 3D general relativistic simulation, our parametrized scheme allows to follow the jet expansion for a very long time and enables us to run many simulations and explore a broad set of global parameters.

The simulations are conducted in 2D axisymmetry. However, even though the calculations are just 2D and not 3D, they are relatively expensive, namely between ~100,000 and 500,000 core-hours per run. This is, first, because we evolve energy-dependent neutrino transport during the first ~0.5 s of evolution, which is roughly an order of magnitude more expensive compared to the purely hydrodynamic case. The second reason is that we need to cover a large range of dynamical timescales, which extends from milliseconds and shorter close to the central black hole up to minutes and hours at radii of about 10^14 cm.

The second part of this project consists of computing the gamma-ray lightcurve of the jet ejecta found in the aforementioned hydrodynamical models. To this end, we employ a Monte-Carlo radiative transfer scheme developed by H. Ito. This scheme is specialized to analyze relativistic jets and has been used previously for analyzing jets resulting in collapsing massive stars.

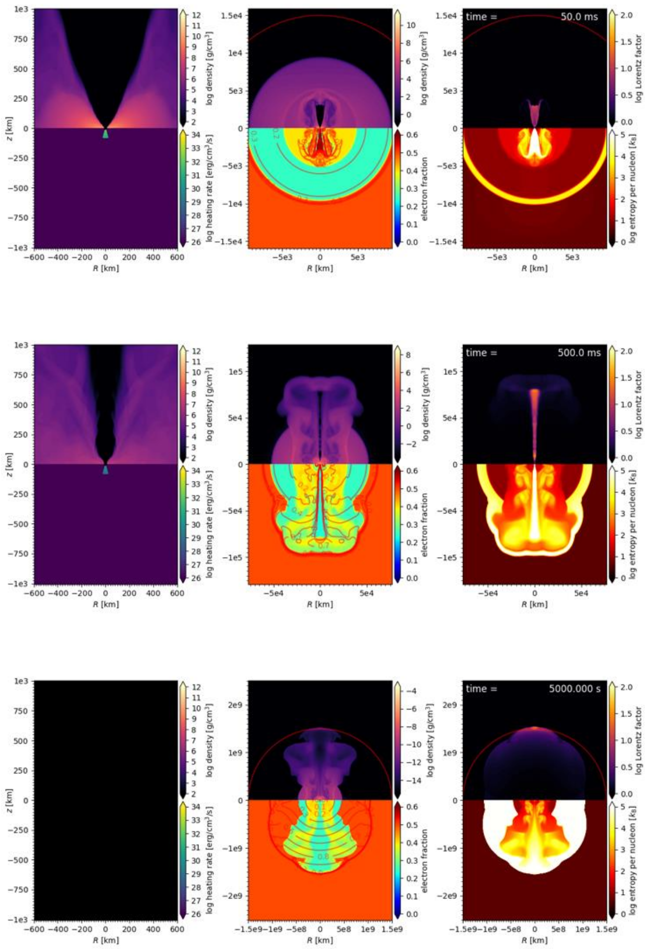

Fig. 1: Snapshots of the disk-jet simulations at 50 ms (top), 500 ms (middle) and 5000 s (bottom) after the start of the simulation showing for each time among others the density (top left, top middle), electron fraction (bottom middle), Lorentz factor (top right), and entropy (bottom right).

3. Result

In Figure 1, we show snapshots of one representative model at three different times. In the top panel taken at 50 ms after the start of the simulation the jet is traveling through the spherical cloud of ejecta, forming a hot cocoon of shocked ejecta material. The middle plot depicts the time (~500 ms) around the breakout of the jet from the ejecta. From this time on the jet is able to expand freely. One can see that apart from the highly relativistic core-component of the jet (close to the symmetry axis), also some modestly relativistic cocoon material breaks free, which later on will contribute to the observable electromagnetic signal. The bottom plot is taken at 5000 s showing the configuration when the highly relativistic core of the jet and its less relativistic wings are in the coasting phase. This is around the time when most of the observable gamma-radiation is emitted (i.e. the phase giving rise to a short gamma-ray burst).

We are currently running an extended set of models testing the sensitivity with respect to the time of black-hole formation, the mass of the torus and ejecta, as well as the power of the jet. We are also presently working on the extraction of the gamma-ray signal using a Monte-Carlo code in a post-processing step. Independently of the gamma-ray signal, we also investigate the impact of the jet on the nucleosynthesis yields. For this purpose we are collaborating with the nucleosynthesis expert Prof. S. Goriely (University Brussels). We have already extracted and provided to Prof. Goriely outflow trajectory data from one of our first simulations. The analysis is ongoing and will be continuously extended by including additional jet models, which are currently running on BW-MPC.

4. Conclusion and prospect for the future

Since we started this project only four months ago, and since one and a half months of this project are still left until it ends, we are unable to present the final results of our study already at this time. However, the simulations performed in this project are the first to describe the disk + jet + gamma-ray signal + nucleosynthesis yields in a single model. We are therefore confident that the calculations done in this project provide enough material for at least to 2 refereed journal papers, one about the gamma-ray signal and another one about the nucleosynthesis yields. Moreover, the models developed here can still be improved in many directions and therefore this project provides a fruitful basis for subsequent investigations.

Fiscal Year 2018 List of Publications Resulting from the Use of the supercomputer

[Oral presentation]

O. Just: "Neutrino hydrodynamical modeling of neutron-star mergers and related nucleosynthesis", Seminar in Department of Astronomy and Astrophysics at University Brussels, January 2019