Usage Report for Fiscal Year 2019

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 merge to form a single compact object surrounded by an accretion disk. Such neutron star mergers for a very long time have 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, finally revealed that neutron-star mergers are indeed sources of short gamma-ray bursts and heavy (so-called r-process) elements. With the dawn of this new era of multi-messenger astrophysics the unique opportunity has become reality to observe and study neutron-star mergers and many connected questions with an unforeseen quality.

However, theoretical models of neutron-star mergers still fall short in explaining a number of important questions, particularly concerning the ultra-relativistic outflow, called jet, that is responsible for producing the sGRB at distances of about 10^{13}-10^{14} cm from the site of the merger. In this project we set out to construct the first simulation models that describe the propagation of the jet all the way from its central engine (consisting of a black-hole accretion disk) to the location where the sGRB is produced. The purpose of the project was two-fold: One aim was to study the impact of the jet on the nucleosynthesis yields of the ejecta through which the jet travels. Another purpose was to compute the sGRB signal of the models and therefore to connect for the first time self-consistently observable features of the sGRB with properties of the central engine.

This project builds upon the previous project G18035, in the course of which we ran the first long-term high-resolution models that laid the basis for the present project.

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 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 by injecting kinetic and internal energy in a parametrized manner to mimic 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 several 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 ~500,000 and 800,000 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.

3. Result

Snapshots of two representative simulation models are shown in Figure 1, namely for one simulation without jet (left) and one with jet (right). The figures show the roughly ellipsoidal shaped dynamical ejecta from the neutron-star merger, in the very center of which sits a black-hole accretion disk that launches a jet. The jet drills a hole through the ejecta and breaks out of the ejecta after a few hundred milliseconds. While traveling through the ejecta, the jet shocks the ejecta and pushes material sideways. The shocked material is called "cocoon" and parts of the cocoon break out of the ejecta together with the jet.

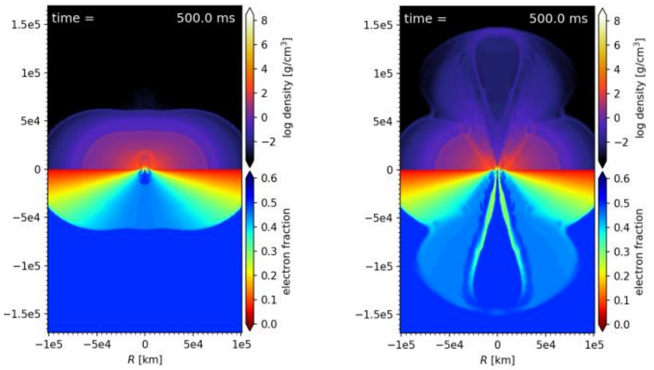

Fig. 1: Snapshots at 500ms after the merger of the density (top) and electron fraction (bottom) comparing two simulations without (left) and with (right) including a jet that is launched from the central black-hole accretion disk system.

A particular focus of our nucleosynthesis study was the shocked cocoon material and the question, which and how many heavy elements can be formed in the cocoon. This part of the project is done in collaboration with the nucleosynthesis expert Prof. S. Goriely (ULB Brussels, Belgium), who post-processed the results of our hydrodynamic simulations. We compared fluid trajectories with and without feeling the impact of the jet. In Fig. 2 the results are shown for two exemplary fluid trajectories, where the jet shocks the trajectory at a time of about 50 ms. The shock increases the temperature (red curve in middle panel) and decreases the density (green curve in middle panel). The enhanced temperatures cause a higher mass fraction of neutrons (purple line in bottom panel). However, the impact on the nucleosynthesis pattern (top panel) is relatively small.

In Fig. 3 the overall impact of the jet summed over all ejecta trajectories (top) and summed only over cocoon trajectories (bottom) is shown. As can be seen, it turns out that the jet only has a minor impact on the abundance pattern. We verified that this result is qualitatively the same for several other models with different ejecta masses and different jet energies.

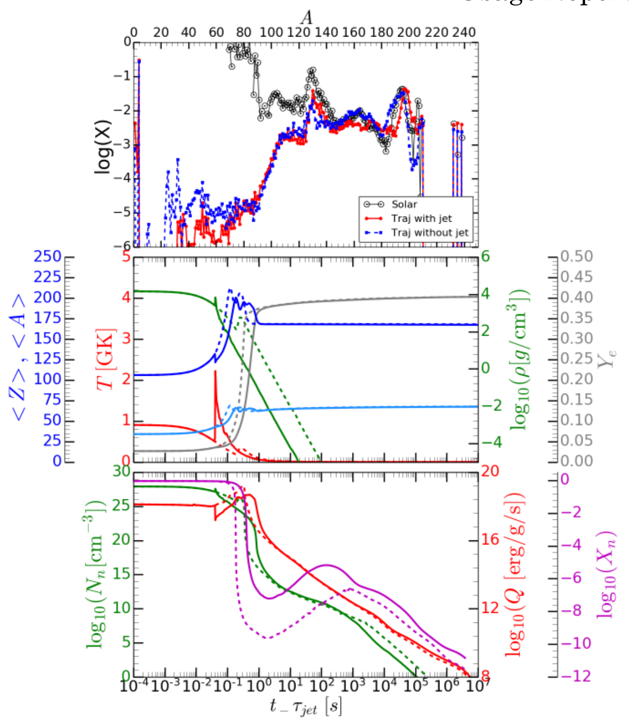

Fig. 2: Comparison of nucleosynthesis yields as function of atomic mass number (top) and thermodynamic properties as function of time between two fluid trajectories with and without jet. In the two lower panels the solid (dashed) lines correspond to the case with (without) jet.

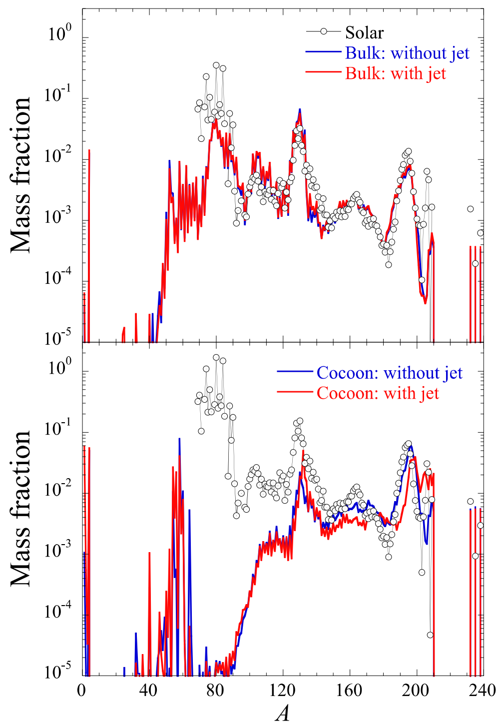

Fig. 3: Nuclear abundance pattern resulting after r-process nucleosynthesis in the ejecta. The top panel shows the abundances summed over all ejecta, while the bottom panel is restricted only to trajectories that are (or would be in case of no jet) in the cocoon.

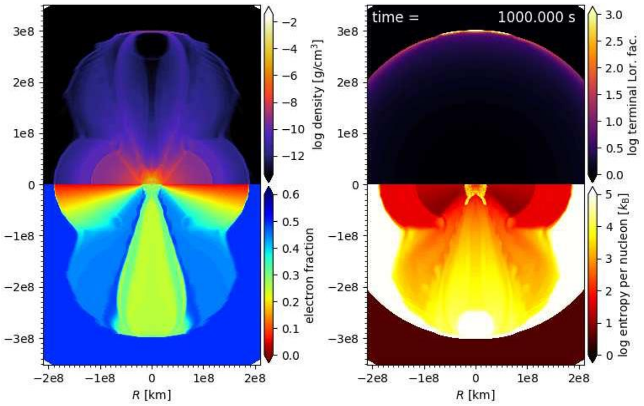

Fig. 4: Snapshots of the post-merger configuration including a jet at 1000 s after the merger showing the density (top left), electron fraction (bottom left), Lorentz factor (top right), and entropy per baryon (bottom right). The sGRB is produced by the thin ultrarelativistic shell visible in the top right panel.

The other major focus of our project, namely the sGRB signal, required us to evolve the hydrodynamical models for much longer times of 1000's of seconds (see Fig. 4 for a snapshot) and with very high resolution in radial direction in order to retain the structure within the ultrarelativistically moving shell. All our planned hydrodynamical simulations are by now finished and the investigation of the sGRB signal via Monte-Carlo post-processing is currently conducted by Dr. H. Ito. We soon expect the first results for the gamma-ray light curve and spectrum of the emitted photons.

4. Conclusion

We have successfully conducted all planned simulations, but the analysis is still going on, particularly for the sGRB signal. Concerning the impact on the nucleosynthesis, however, we can already say that the jet does not have a bit impact. This result has an important implication, namely that all existing nucleosynthesis models of neutron-star mergers that do not include a jet retain their credibility. I.e. modeling the jet is not necessary to obtain accurate nucleosynthesis predictions.

5. Schedule and prospect for the future

Simulating jets together with the central engine is numerically challenging and computationally expensive. Most existing studies therefore cut out and ignore the central engine. In the course of investigating our models, which for the first time include the central engine, we encountered several unforeseen difficulties with the numerical scheme and with the prescription of injecting the jet. We also stepped over several intermediate questions that needed to be addressed by setting up additional test models. Therefore, the progress of the project was somewhat delayed. Within the next months we plan to publish the results in two peer-reviewed papers, one on the nucleosynthesis and another one on the sGRB signal. Also, we plan to investigate whether the jet has an impact on the optical and infrared (so-called kilonova) emission.

Fiscal Year 2019 List of Publications Resulting from the Use of the supercomputer

[Conference Proceedings]

O. Just, A. Bauswein, S. Goriely, H. Ito, H.-Th. Janka, S. Nagataki: "How to interpret observations of neutron-star mergers?", IOP Proceedings, 2019, accepted

[Oral presentation]

O. Just: "Role of Neutrinos in Neutron-Star Mergers", Japan-Israel Meeting in High-Energy Physics, July 2019, RIKEN

O. Just: "How to deal with neutrinos in simulations of neutron-star mergers and core-collapse supernovae?", Nuclear and Astrophysics Aspects for the R-Process, July 2019, Trento, Italy

O. Just: "What can we learn about the r-process and nuclear equation of state from neutron-star merger observations?", GSI FAIRNESS Workshop, May 2019, Genova, Italy

[Poster presentation]

O. Just, SPDR poster session, presentation of research results (awarded with SPDR poster prize)