Usage Report for Fiscal Year 2021

Project Title:

Two- and three-dimensional neutrino-hydrodynamics simulations of hyper-massive neutron stars

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

If two neutron stars revolve around each other in the form of a binary, they continuously loose energy and angular momentum in the form of gravitational waves. They will very slowly approach each other and, ultimately, will fall into each other and merge to form a single object, a so-called hypermassive neutron-star (HMNS), which may either collapse into a black hole (BH) on timescales of milliseconds or longer or may remain indefinitely stable. The recent observation of the collision of two neutron stars in the event called GW170817 was the first of its kind and sparked tremendous attention within the scientific community. This is because very important questions are connected to neutron-star mergers: What is the origin of about half of the heavy elements heavier than iron, those produced by the so-called rapid-neutron-capture (or r-) process? And, what is the origin of short gamma-ray bursts (sGRBs)?

Since GW170817 we now almost certainly know that a substantial fraction of heavy elements must have been created in the outflows of binary neutron-star mergers that occured during the past evolution of the Universe. This spectacular confirmation of existing theoretical models was possible, because material ejected in neutron-star mergers shines extremely bright and so could be observed in the form of a so-called Kilonova for several days after the merger. However, even though GW170817 was providing bright electromagnetic signals, it remains unclear how to exactly interpret these signals, particularly the red and blue kilonova. Lightcurve analyses of GW170817 predict that the bright blue kilonova is associated with ejected material of a few per-cent the mass of the sun and velocities of 10-30 per-cent the speed of light, while the red kilonova is believed to originate from another ejecta component with higher photon opacities. Although a growing number with exceedingly more sophisticated models of neutron-star mergers and their remnants already exists, a safe identification of the origin of each observed ejecta component is not possible at this moment. It is currently believed that the blue shining material is launched by a hyper-massive neutron star, but no available simulation is credible enough, yet, to scrutinize this hypothesis.

The original purpose of this project was the investigation of HMNSs. While work on this project is still ongoing, the computational budget was used also to perform simulations of the long-term evolution of ejecta and of jets and is related to projects by Hirotaka Ito and Yuki Takei (Q21542).

2. Specific usage status of the system and calculation method

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

We typically run the code, which adopts a hybrid OpenMP + MPI parallelization, on 10-16 compute nodes.

3. Results and conclusions

The computations performed in the course of this fiscal year were used to improve HMNS models (still unpublished) and provide input for two publications.

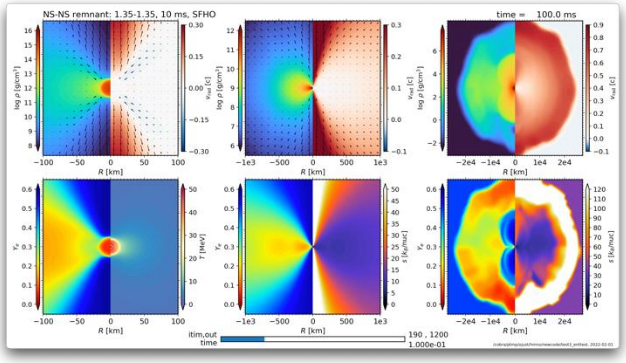

Fig. 1: Snapshots of various quantities in a simulation of a HMNS at about 100 ms after the merger.

Snapshots of a 2D HMNS simulation are shown in Fig. 1. Our simulations exhibit a powerful, high-velocity neutrino-driven wind along the polar directions and a relatively slow outflow along the equatorial directions. The material is neutron rich along the equator and proton rich along the poles. We are currently investigating the dependence of the properties of these winds on the viscosity scheme that is adopted in the HMNS.

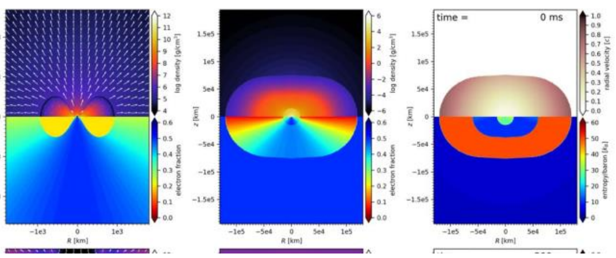

Fig. 2: Snapshots of the jet model used as input for a radiative transfer calculation to predict the prompt sGRB signal.

Apart from the HMNS simulations, the computational budget was also used to provide the input model of the long-term evolution of jets for a related project by Hirotaka Ito, who computed the sGRB signal of the jet using a sophisticated gamma-ray Monte Carlo scheme (see Fig. 2). This study, which is published in The Astrophysical Journal, is the first to present a global numerical model that follows the jet all the way from the central BH-torus system on length scales of a few kilometers out to the radius of the gamma-ray emission at about 10^8 kilometers and which uses a relativistic Monte-Carlo radiative transfer scheme to predict the photospheric emission of the prompt GRB signal. The study demonstrated that the emission is strongly angle dependent, with a high-luminosity core and low-luminosity off-axis emission. The low luminosity at large observation angles suggests that the observed sGRB from the recent event GW170817 did most likely not originate from ordinary photospheric emission, but from the emission released during the sudden breakout of the shock that is pushed in front of the jet.

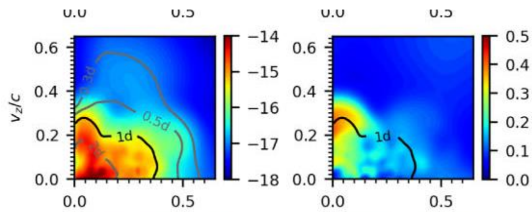

Fig. 3: Contours of the density (left) and electron fraction (right) of dynamical ejecta produced in NS mergers. The solid lines denote the photospheres at different times.

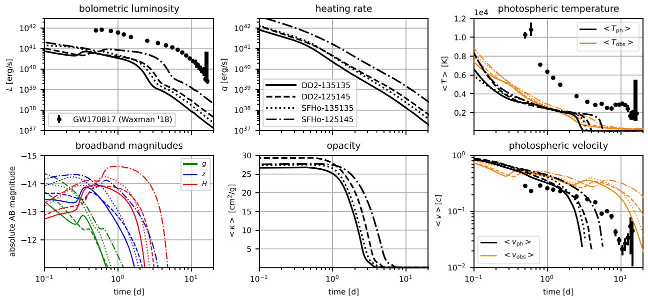

Fig. 4: Various quantities as functions of time characterizing the kilonova light curves for the dynamical ejecta.

Finally, a small part of the computational budget was used to perform calculations of the kilonova signal that emerges from the early, dynamical ejecta in NS mergers. To this end, we developed a new, approximate kilonova scheme that is based on the two-moment radiative transfer with a local M1 closure. We gauged this scheme by comparing with sophisticated Monte-Carlo solutions. In the study we found that the kilonova signal (Fig. 4) from the dynamical ejecta (Fig. 3) is too dim and has too low spectral colors compared to GW170817. This suggests that other ejecta components are more likely to be responsible for the observed signal in GW170817.

4． Schedule and prospect for the future

In the future we plan to take the next step from 2D axisymmetric models to full 3D simulations of the HMNS and the jets.

Fiscal Year 2021 List of Publications Resulting from the Use of the supercomputer

[Paper accepted by a journal]

[1] Hirotaka Ito, Oliver Just, Yuki Takei, and Shigehiro Nagataki, *"A Global Numerical Model of the Prompt Emission in Short Gamma-ray Bursts"* The Astrophysical Journal, 918, 59 (2021)

[2] Oliver Just, Ina Kullmann, Stephane Goriely, Andreas Bauswein, Hans-Thomas Janka, Christine Collins, *"Dynamical ejecta of neutron star mergers with nucleonic weak processes -- II: kilonova emission"* Monthly Notices of the Royal Astronomical Society, Vol. 510, 2820 (2022)

[3] Oliver Just, Stephane Goriely, Hans-Thomas Janka, Andreas Bauswein, *"Neutrino absorption and other physics dependencies in neutrino-cooled black hole accretion discs"* Monthly Notices of the Royal Astronomical Society, Vol. 509, 1377 (2021)

[Others (Book, Press release, etc.)]

[4] Press release at GSI Darmstadt based on paper [3],

URL: https://www.gsi.de/en/start/news/details/2021/11/15/elementsynthese-schwarze-loecher

[5] Article in a german popular science journal "Sterne und Weltraum" based on paper [3],

URL: https://www.spektrum.de/magazin/wie-schwarze-loecher-gold-schmieden/1975711