Usage Report for Fiscal Year 2020

**Project Title:**

## Improved hydrodynamical simulations of gamma-ray burst central engines

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

Massive stars with masses of more than 8 solar masses explode as supernovae at the end of their lives. As a result of this explosive event, a neutron star or a black hole is formed at the center. If two neutron stars are in a binary system, gravitational waves (GWs) continue to be emitted and take away their energy. Hence it follows that they finally merge together to become a single compact object after a long period (neutron-star merger event). If the surrounding matter accretes on it, a relativistic jet can be launched from the merger remnant, which could explain the long mysterious short gamma-ray bursts (sGRBs).

Thanks to the enormous efforts to detect GW signals from merger events by LIGO and Virgo, the recent GW observation of a neutron-star merger, GW170817, together with the observation of an sGRB finally confirmed that the central engines of sGRBs truly are neutron-star mergers. The spectacular event marked the dawn of multi-messenger astronomy, in the framework of which a single event can be seen through various signals: GWs, radio, optical, infrared, and gamma-ray radiation.

However, many aspects and questions still remain open, particularly concerning the jet. In our previous project, we ran one simulation and generated the fiducial model that served as the input for sGRB calculation. We found that the time resolution was not sufficient for calculating sGRB signals. In this General Use project G20026, we try to run the simulation with the time resolution 10 times higher than the previous one. We also focus on the jet opening angle and aim to reproduce the observations. Our models are one of the first models of GRB jets that simultaneously follow the evolution of the accretion disk.

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. This is the same method as the one that was used in the previous project.

3. Result

We ran one 2D simulation with very high time resolution in order to allow the accurate calculation of the GRB light curve by Hirotaka Ito (see Quick Use project Q20362). One aim of the GRB calculation is to test the Yonetoku relation between $L_{\rm peak}$ and $E_{\rm peak}$ of the GRB. Preliminary results show that our models can explain well the Yonetoku relation.

We find that the fiducial model exhibits a jet with a rather small opening angle compared to observations. In order to investigate the physics of the jet collimation, which determine the opening angle of the jet, we are currently running an extensive set of models. We change the initial torus mass $M$, the luminosity of the injected jet $L_j$, as well as the specific enthalpy $h$, and opening angle $\theta_{\rm ini}$ of the injected jet. Although this is ongoing work, we currently believe that the jet collimation is a result mainly of the interaction of the jet with the winds driven by the disk. In order to test this hypothesis, we run several models ignoring the torus entirely. In order to get a wider opening angle of the jet that is more consistent with observations, we also increase the jet luminosity $L_j$. Moreover, we test the sensitivity of the prompt GRB signal on the final jet Lorentz factor by increasing the initial specific enthalpy $h$.

In Figure 1, contour plots of the Lorentz factor for the fiducial model at different times are shown. As the parameter set for the fiducial model, we choose $h$ = 100, $L_j$ = $10^{50}$ erg/s, $\theta_{\rm ini}$ = 10°, $M$ = $10^{-2}$ $M_\odot$. For testing the dependence on the parameters, we choose the following 6 sets of parameters, ($h$, $L_j$, $\theta_{\rm ini}$, $M$) = (100, $10^{50}$ erg/s, 15, $10^{-2}$ $M_\odot$), (100, $10^{50}$ erg/s, 25, $10^{-2}$ $M_\odot$), (300, $10^{50}$ erg/s, 10, $10^{-2}$ $M_\odot$), (100, $3\times10^{50}$ erg/s, 10, $3.3\times10^{-3}$ $M_\odot$), (300, $3\times10^{50}$ erg/s, 10, $3.3\times10^{-3}$ $M_\odot$), (100, $10^{50}$ erg/s, 10, $3.3\times10^{-3}$ $M_\odot$).

## 4. Conclusion

In this project, we successfully conduct the simulation with finer time resolution and hand over it to the code of calculating sGRB signal, for which a paper is in preparation. Hirotaka Ito is now investigating our high-time resolution model, and preliminary results show that our models can explain well the Yonetoku relation. We still continue to run the simulations under variation of several parameter sets. These runs are supposed to explore the jet opening angle and the question whether our models could explain observed sGRBs.

## 5. Schedule and prospect for the future

This study is work-in-progress, but it will ultimately be the input for 2 papers, one investigating the GRB signal, and another one investigating the jet opening angle. If we find appropriate configurations on parameter sets to reproduce observations, then we will hand over the simulation data to the code of calculating sGRB signals, which Hirotaka Ito developed. This will lead us to deeper understanding of neutron-star merger events.

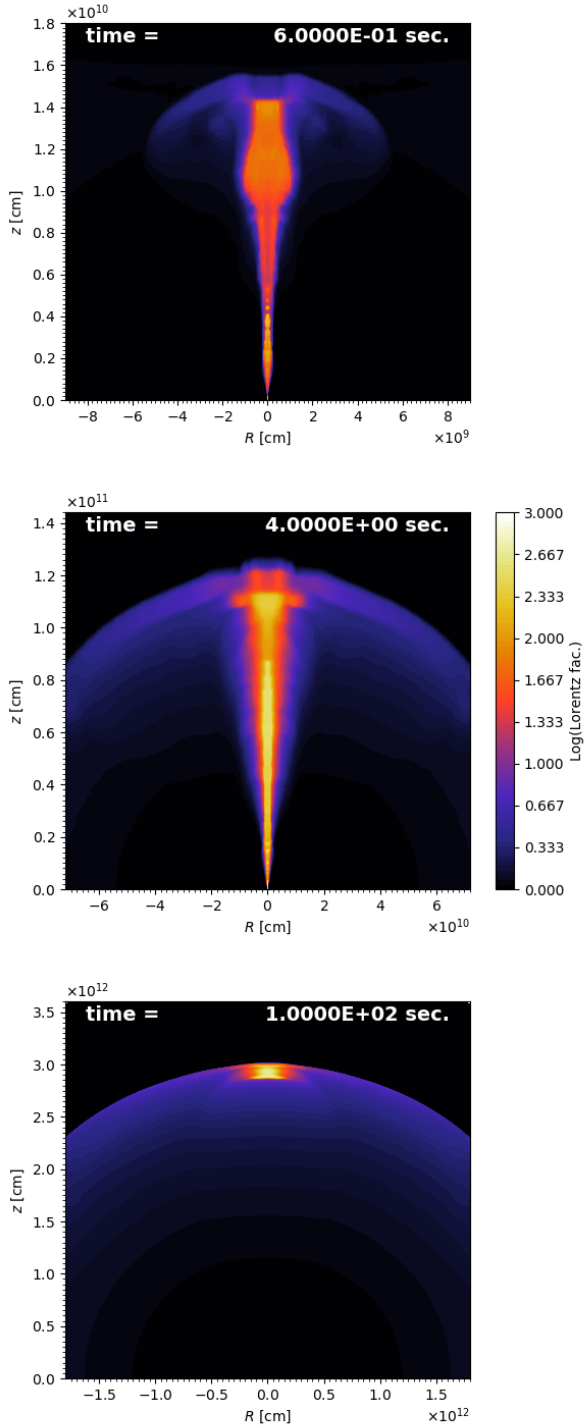


Figure 1: Snapshots of the Lorentz factor for the fiducial model at $t$ = 0.6, 4, 100 seconds from the merger (top, middle, bottom panel, respectively).