Usage Report for Fiscal Year 2021

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

A massive star with mass of more than 8-10 solar masses explodes at the final stage of its evolution, which results in the formation of a black hole or a neutron star at the center. If these compact remnants are in a binary system, gravitational waves (GWs) take away the energy and thus the orbit continues to shrink. Finally, they merge to be one compact object, the moment of which can be observed by gravitational wave telescopes such as those at LIGO and Virgo. If there exists the surrounding matter and it accretes on the object, it is possible that a relativistic jet is launched from it. Theoretically, this process could be one of the origins of short gamma-ray bursts (sGRBs).

On 17th August 2017, LIGO and Virgo have first detected GWs emitted from a binary system consisting of two neutron stars at ~40 Mpc from Earth (GW170817). Surprisingly, a sGRB was observed simultaneously at the same position (named as GRB 170817A). These events reveal that neutron star-neutron star mergers are the central engines of sGRBs. The successful detection of GW signals thus opens the door to multi-messenger astronomy (GWs, neutrinos, radio, optical, infrared, X-rays, and gamma-rays).

However, the research of neutron star-neutron star mergers is still at a rather early phase and many aspects are only poorly understood, particularly concerning the jet. In our previous project G20026 and current one Q21542, we ran one 2-D simulation with very high time resolution for Hirotaka Ito to calculate GRB signals accurately. We find that our jet model successfully reproduces the Yonetoku relation between the peak luminosity $L_{\rm peak}$ and the peak energy of the spectrum $E_{\rm peak}$ of the GRB (see publication [1]). We also find that the initial configuration we used in the run makes the opening angle of the jet quite narrow compared to the values obtained by observations. We aim at searching for parameter spaces that give wider opening angle of the jet in our current project Q21542.

2. Specific usage status of the system and calculation method

We used the same method as the one that was used in the previous related project (see also the report for General Use G20026). We rewrite the method in the following; 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.

We fully consumed the total allocated CPU time by conducting a lot of 2-D simulations of relativistic jets (~3,800,000 CPU hours). At each run, 1,280 (32 nodes × 40 cores) or 640 (16 nodes × 40 cores) cores were used depending on the treatment of neutrino transport in the code.

3. Result

We ran several simulations changing the following parameters; the torus mass $M_{\rm disk}$, the ejecta mass $M_{\rm ej}$, the injected energy rate (jet luminosity) $L_{\rm j}$, the initial opening angle of the jet $\theta_{\rm ini}$.

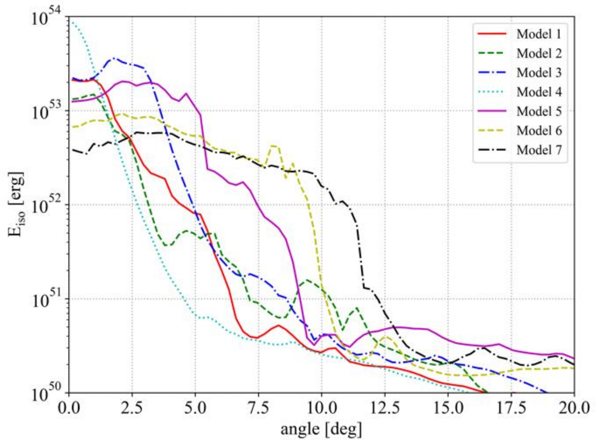

Figure 1: Distributions of the isotropic energy as functions of the angle.

We show the distribution of the isotropic energy E_{iso} for 7 models in Figure 1. Models with parameter sets (M_{disk}, M_{ej}, L_j, θ_{ini}) = (0.044, 0.04, 10^{50}, 10°) (Model 1), (0.044, 0.04, 10^{50}, 25°) (Model 2), (0.015, 0.04, $3{\times}10^{50}$, 10°) (Model 3), (0.015, 0.04, 10^{50}, 10°) (Model 4), (0.015, 0.04, 10^{51}, 10°) (Model 5), (0.015, 0.013, 10^{51}, 10°) (Model 6), and (0.015, 0.013, 10^{51}, 15°) (Model 7) are shown. Here M_{disk}, M_{ej}, L_j, are written in the unit of solar masses, solar masses, and erg/s. As can be seen in the figure, E_{iso} is quite large around the core and declines rapidly with the angle. We also plot the distribution of the Lorentz factor Γ as function of the angle for models 1-7 in Figure 2. We define the opening angle of jets as the region where the Lorentz factor exceeds 100. $\Gamma \gg 100$ near the center, while there exists a steep 'cutoff' in each model. The location of this cutoff, namely the opening angle, highly depends on selected parameters. We find that the opening angle becomes wide for smaller ejecta mass by the comparison of model 1 with models 6 and 7. It is also found that the higher jet luminosity makes the opening angle wider (from the comparison of model 1 with models 3 and 5). The opening angle also depends on the combination of parameters. For instance, compare the model 2 with model 1. Both models show the same opening angles (~2.5°), although the initial opening angle is set to 25° in model 2. On the other hand, the opening angle of model 7 where the ejecta mass is smaller than that in model 1 is wider than that of model 6, although the difference between them is only the initial opening angle. This comparison suggests that the dependence of the opening angle on the initial opening angle may vary with ejecta mass and/or torus mass.

The opening angle of jets is found to be within ~16°±10° by observations of sGRBs (Fong et al. 2015). On the other hand, the opening angle suggested by the observation of GRB 170817A is ~3.4°±1° (Ghirlanda et al. 2018), or ~4° (Mooley et al. 2018). Our preliminary results suggest that this discrepancy arises from the difference of the ejecta mass. We are now running more simulations changing the ejecta mass for fixed other parameter sets.

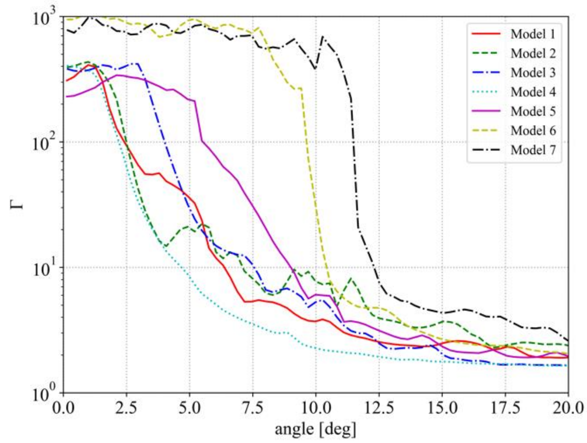

Figure 2: Distributions of the Lorentz factor as functions of the angle.

4. Conclusion

In this project, we search for the dependence of the opening angle of jets on parameters such as the injected energy rate, the torus mass, the ejecta mass, and the initial opening angle by doing an extensive set of 2-D simulations. We find that the jet shows wider opening angle if the ejecta mass is larger regardless of the choice of other parameters except for the injected energy rate. In contrast, if the ejecta mass is smaller, the dependence of the opening angle on parameters becomes complicated. The initial opening angle may play an important role in the opening angle in this situation. We will confirm this by other simulations currently running.

5. Schedule and prospect for the future

If we find appropriate parameter spaces that gives the opening angle suggested from observations, we will hand over the profiles of the jet to Hirotaka Ito and do sGRB simulations to check whether the sGRB signal matches the observation as well. By doing so, we will get one step closer to understanding the nature of neutron star-neutron star mergers.

We also plan to extend our research to 3-D simulations by which we can avoid the accumulation of heavy ejecta which remains on the top of the jet with the approximation of axial symmetry (Harrison et al. 2017, Gottlieb et al. 2018).

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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, Vol. 918, id. 59, 2021