9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Three-Dimensional General Relativistic Radiation Magnetohydrodynamic Simulations of Supercritical Accretion onto a Magnetized Neutron Star

Akihiro Inoue[1], Ken Ohsuga[2], Hiroyuki R. Takahashi[3] and Yuta Asahina[2,3]
[1] Department of Earth Science and Astronomy, University of Tokyo, [2] Center for Computational Sciences, University of Tsukuba, [3] Department of Natural Sciences, Faculty of Arts and Sciences, Komazawa University
e-mail (speaker): inoue-a@g.ecc.u-tokyo.ac.jp

Ultra-Luminous X-ray sources (ULXs) are bright, point-like X-ray sources whose luminosity exceeds 10^{39} erg s^{-1}. To understand the powering mechanisms of the ULXs, we have performed three-dimensional general relativistic radiation magnetohydrodynamic simulations of supercritical accretion flows onto a neutron star (NS) with dipole magnetic fields. Our models show that non-axisymmetric flows develop around the magnetized NS (Figure 1), which may originate from the magnetic Rayleigh-Taylor instability. The resulting radiation luminosity can explain a large luminosity observed in ULXs. In this talk, we also show that the NS acquires a large angular momentum from the accretion disk, which leads to a significant spin-up of the NS.

The large luminosity in the ULXs indicates that they are powered by either subcritical accretion onto intermediate-mass black holes, supercritical accretion onto stellar-mass black holes, and/or supercritical accretion onto neutron stars (NSs). [1] Some ULXs exhibit coherent pulsations with a period of ~ 1 s. [2] These pulsations indicate that a fraction of ULXs is powered by the supercritical accretion onto a magnetized NS.

Several studies investigated the NS-powered ULXs through two-dimensional general relativistic radiation magnetohydrodynamic simulations. [e.g., 3,4,5] These studies revealed that the supercritical accretion onto a magnetized NS can explain the observations. However, it has been pointed out that the accretion flows around the magnetized star is unstable for the magnetic Rayleigh-Taylor instability. [e.g., 6] The instability will lead to the non-axisymmetric accretion flows. Therefore, three-dimensional simulations are necessary for understanding the ULXs.

The simulation setup is as follows. We have initialized the system with an axisymmetric equilibrium torus whose rotation axis coincides with the NS's magnetic axis. We set a maximum gas density of the initial torus of 0.1 g cm^{-3}. We investigate two cases where the dipole field strength at the NS surface is $B_{\rm NS} = 10^{10}$ G and 10^{11} G. These setup result in the supercritical accretion flows with a mass accretion rate of $\sim 10^{20}$ g s^{-1}.

Figure 1 illustrates the volume rendering of the gas density for $B_{\rm NS} = 10^{11}$ G. White lines stand for the magnetic field lines. The non-axisymmetric accretion flows appear inside the inner edge of the disk. At the vicinity of the NS, column accretion flows also form along the dipole field lines. The flows are called accretion columns and are the main radiation source. The resulting radiation luminosity is $\sim 10^{40}$ erg s^{-1}.

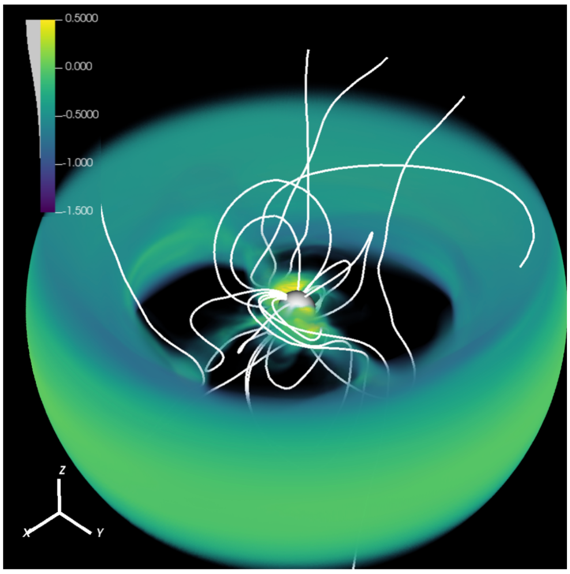

Figure 1. Volume rendering of the gas density and magnetic field lines (white lines). The white sphere represents the NS surface. We illustrate the case of $B_{\rm NS} = 10^{11}$ G. Non-axisymmetric flows appear around the NS.

We have compared the three-dimensional models with the two-dimensional models. We have found that the angular momentum flux transported to the NS is greater in the three-dimensional model than in the two-dimensional model.

This work was supported by JSPS KAKENHI Grant Numbers 24KJ0143, 25K17439 (A.I.), 21H04488, 24KF0130 (K.O.), 24K00678 (H.R.T) and 23K03445 (Y.A.). Numerical computations were performed with computational resources provided by Cray XC 50 at the Center for Computational Astrophysics (CfCA) of the National Astronomical Observatory of Japan (NAOJ).

References

[1]. P. Kaaret, et al, ARA&A, **55**, 303 (2017)
[2]. M. Bachetti, et al, Nature, **514**, 202 (2014)
[3]. H. R. Takahashi & K. Ohsuga, ApJL, **845**, 9 (2017)
[4]. A. Inoue, et al, ApJ, **952**, 62 (2023)
[5]. A. Inoue, et al, ApJ, **977**, 10 (2024)
[6]. A. K. Kulkarn & M. M. Romanova, MNRAS, **286**, 673, (2008)