High-resolution magnetohydrodynamic simulations of two-temperature jet propagation using code CANS+

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Jet launched from an active galactic nucleus provides a large amount of energy to the surroundings through shocks and turbulence. As a result, jet-driven turbulence inhibits the growth of the host galaxy by suppressing the mass accretion onto it. Therefore, the jet plays a major role in galactic evolution and the history of the structure formation of the universe. However, the physics of the interaction between the jet and the surrounding environment is still poorly understood.

In this study, we focus on the jet stability. The jet is a magnetized supersonic flow, which is a magnetohydrodynamic (MHD) unstable system because of the velocity shear with the surroundings. In particular, it has been pointed out that the development of the Kelvin-Helmholtz (KH) instability, Rayleigh-Taylor (RT) instability, and current-driven kink instability influence jet dynamics. The nonlinear growth of these instabilities depends not only on the internal structure of the jet itself but also on the surrounding environment. However, since the surrounding environment is determined by the cocoon which is a by-product of a propagating jet, it is finally necessary to solve the jet propagation problem.

On the other hand, the two-temperature nature of the plasma is an important physics in the system of jets and surroundings. In the high-density and low-temperature gas, the electron and proton temperatures become equal instantly by Coulomb collisions. Thus, the large-scale plasma dynamics can be treated as a single-temperature fluid. In contrary to this, when the plasma temperature is reached electron relativistic temperature, this picture changes. The Coulomb coupling becomes inefficient, and the electrons and protons can have a different temperature, i.e. plasma has "two-temperature". Thus, we should solve the thermodynamics equations for both electrons and protons to deal with two-temperature plasma.

Numerous numerical simulations have been performed to study the basic structure and stability of the propagating jet. However, due to the limitation of the numerical resources, the simulation box size only reaches 100 times the initial jet radius. Also, the two-temperature nature of the plasma has been ignored in the previous studies. Therefore, by using high-order MHD code CANS+ and the supercomputer "Fugaku", we aim at the high-resolution and two-temperature MHD simulation which follows the long-term jet propagation to 1000 times of the initial jet radius. As a result, we can connect the multilayer structure from sub-kpc to hundred kpc scale in one calculation. At present, we have been conducted test simulations that the jet propagates at the spatial scale of 300 times the initial jet radius by using "Fugaku".

We first report our previous results of two-temperature simulations with the different jet magnetic energy to investigate the effect of jet dynamics and electron heating. strongly magnetized jet suffered from current-driven kink mode. Meanwhile, weakly magnetized jets were decelerated by the high-mixing ratio between the jet beam and cocoon gas, which were induced by KH and RT instability. Also, jet magnetization affected the distribution of magnetic fields. The turbulent scale of the weakly magnetized jet was shorter than that of the strongly magnetized jets since the magnetic tension suppressed the turbulence motion. Through the three-dimensional studies, we found that there are two steps for the thermodynamics of electron and proton in the evolution of jet: First, most of the bulk kinetic energy of the jet is converted into thermal energy of proton through shocks, which are formed in the jet beam. Second,

while magnetic fields are relatively strong, shocked-electrons stored in the cocoon evolve toward energy equipartition with magnetic energy through turbulent dissipation. In this presentation, in the addition to these results, we report the progress results by using "Fugaku".

