国立天文台天文シミュレーションプロジェクト 成果報告書

AGN Feedback Model in GADGET3-Osaka: Isolated Galaxy

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As the most massive kind of celestial objects, supermassive black holes (SMBHs) in galactic nuclei play a significant role in galaxy evolution. Feedback released by active galactic nucleus (AGN) is believed to be responsible for some observational issues, e.g. correlation of SMBH mass to its host galaxy velocity dispersion and total stellar mass, star formation quenching, intracluster medium (ICM) heating, and the downsizing of observed galaxies at lower redshifts. While the observations data clearly show evidence of the importance of AGN, the physics behind this kind of phenomena and how this processes are actually happening are still unclear until this day.

Considering the significance of AGN feedback in galaxy evolution, a great effort is made by the astronomical community to study the effects of AGN both theoretically and through simulations. While observational results obtained in various wavebands have given us a decent insight of AGN processes, numerical simulations with comprehensive physics are essential to decipher how AGN feedback actually works and to test out our current understanding of galaxy formation and evolution. In this research, we have been trying to develop our GADGET3-Osaka code to simulate AGN feedback and SMBH evolution, and see if the results we get are in good agreement with the data obtained from observations.

Difficulties in Implementing AGN Feedback

We need to emphasize the difficulties in implementing AGN Feedback and how we deal with them. AGN feedback involves a wide span of spatial scale, starting from AU/sub-AU scale (accretion disk, jet, dusty torus, etc.) up to kpc/Mpc scale (galaxies, ICM, clusters, etc.). Creating a simulation with all of this scales resolved requires a lot of computational resources and time. As we are aiming for cosmological simulation, we try to skip the small scale processes by introducing sub-grid physics. All processes that occur below the resolution are evaluated semi-analytically and the resulting physics apply to the large scale directly. In this research project, we introduced new sub-grid model for AGN feedback processes. Instead of using simple kernel distributed thermal feedback, we present two modes of AGN feedback according to observations, i.e. quasar mode (high mode) and radio mode (low mode). In quasar mode, we use geodesic dome bins to assign feedback energy to the surrounding gas particles. In radio mode, we use propagating gradual feedback with cylindrical bins to emulate the result of radio jet from a black hole without actually creating the jet itself which is computationally costly.

Code Development

As for the quasar mode, here are the details of how we implement the feedback. Instead of using the old kernel-weighted method, we use geodesic dome bins (in this case, truncated icosahedron (Fig. 1)) to assign energy. Kernel-weighted function allocate more energy to high density region which may lead to uneven energy distribution and energy loss due to stronger cooling effect in high density gas. Radius of this geodesic dome is proportional to the feedback travelling speed, i.e. speed of light, and simulation time step. Gas particles within the same bin will share the same amount of energy, while energy assigned to each bins is in proportion to their volume. In such a way, energy can be distributed evenly to all direction. The denser gas in certain direction is, the less energy each gas particles will receive. With this scheme, we can expect the energy to transfer more efficiently through lower density region. The amount of energy injected to gas particles follows the same rule as in the references, i.e. converting a fraction of accreted mass into energy using Einstein's mass energy equivalence equation. Then, a fraction of this energy is converted into thermal energy.

For the radio mode, we are interested in simulating strong jet feedback from the SMBH. However, it requires very high resolution which is not suitable for our future research. Instead, we intend to recreate jet feedback without actually injecting jet into circum-galactic medium (CGM) or ICM, and just distributing energy along the pathway of this 'jet particles' which we call as ghost (gas host) from now on. We call it so because that gas particles will host this jet feedback (Fig. 2). Instead of dumping the energy all at once to certain direction, we inject only a fraction of it to a cylindrical bin depending on the density at that point and pass over the remaining energy to the next ghost in the same direction. This process continues to go on emulating a jet-like feedback throughout the simulation and will work well even in low resolution.

Current State of Our Research

At this state of our research, we are still performing test-run simulation with simple isolated galaxy case. The initial condition of this isolated galaxy is adopted from AGORA project initial condition. As we are going to analyze AGN feedback effects not just to the host galaxy, but also to the CGM and ICM, we add gaseous halo by converting a fraction of dark matter halo mass into gas and set the temperature to around 10^6 K. We have compared the impact of AGN feedback on CGM and star formation in the galaxy between these three models, i.e. quasar mode, radio mode, and simple kernel-weighted model. Note that strong feedback is given by quasar mode feedback and kernel-weighted model suppressed black hole growth the most as it heats up high density gas thus preventing further accretion. Next step of our research will be more generalized cases, including galaxy mergers and cosmological simulation. However, we will need to implement black hole and galaxy formation first before we are going any further.

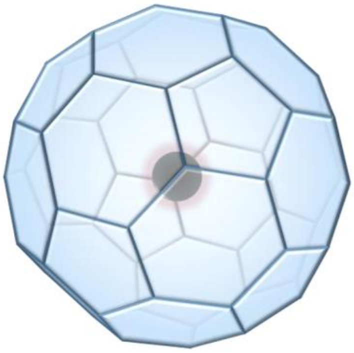

Figure 1. Truncated icosahedron bins.

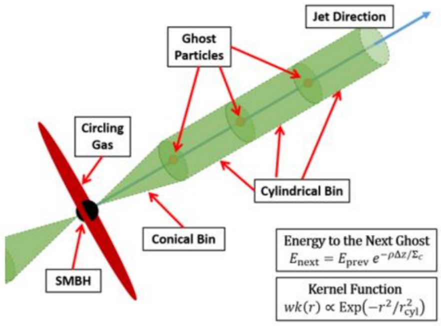

Figure 2. Jet feedback using ghost scheme.

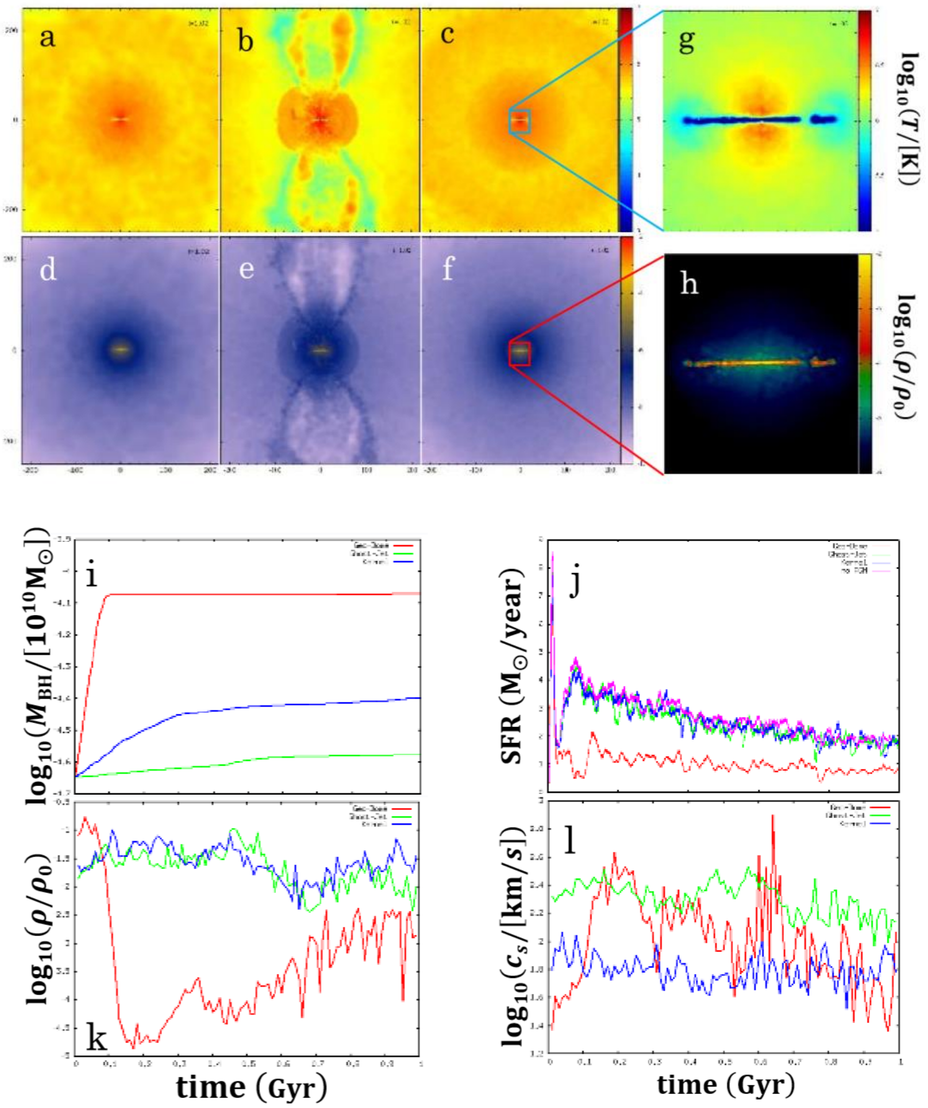

Figure 3. Temperature plot for **(a)** kernel-distributed feedback, **(b)** quasar mode and **(c)** radio mode, and their corresponding density plot **(d)**, **(e)**, and **(f)** at t = 1 Gyr (width 420 kpc). **(g)** **(h)** Zoomed-in plot for radio mode (width 42 kpc). Evolution of **(i)** SMBH mass, **(j)** star formation rate (SFR), and **(k)** gas density and **(l)** sound speed around the black hole. (red: geodesic dome, blue: ghost, green: kernel). Note: $\rho_0 = 6.77 \times 10^{-22}\mathrm{g/cm}^3$

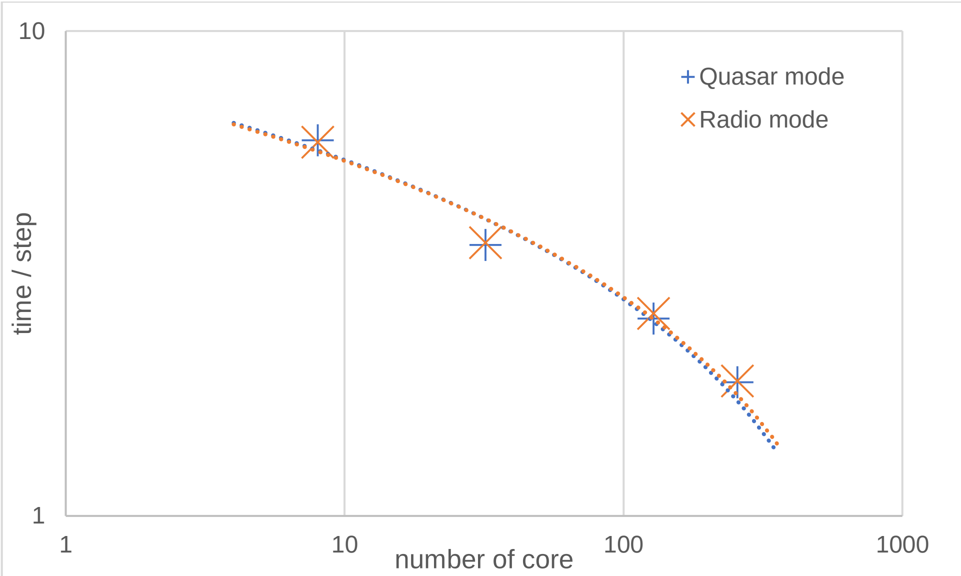

Figure 4. Calculation time per step using quasar mode (blue) and radio mode (orange).
The horizontal axis represents the number of cores used.