The complex evolution of AGN outflows:

Challenges of simulating and interpreting observations of AGN activity

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Abstract

Understanding the influence of AGN activity upon the surrounding medium on scales ranging from sub-parsec to several kiloparsecs is one of the main Athena science goals. In order to interpret the observations, we need to understand the expected variety of effects that AGN radiation and winds can have. These include suppression of SMBH feeding, compression and expulsion of gas and so on. High-resolution numerical simulations can help us gain these insights, but they have limitations imposed by numerical resolution, subgrid prescriptions and the stochastic nature of some processes, such as gravitational collapse. Here, I present the results of three studies designed to evaluate the importance of these effects and suggest how to alleviate these problems.

Stochasticity

(Zubovas 2015, MNRAS, arXiv: 1505.05464)

Certain physical processes, such as the growth of gravitational instabilities, are strongly stochastic. When modelling these processes, it is difficult to ascertain which results arise due to stochastic variations and which are robust.

To illustrate this issue, I ran four SPH simulations [1] of an idealized 200-pc-radius rotationally supported nuclear gas disc affected by a 0.7-Myr-long burst of $L = 5{\cdot}10^{44}$ erg/s AGN activity. The only difference among the models is the positions of the individual particles. Each model was evolved for 6 Myr in total. The AGN feedback is assumed to be in the form of a quasi-relativistic wind ($v = 0.1c$), which does not disperse the disc gas, but only compressed it. The resulting morphologies of the four models are shown below.

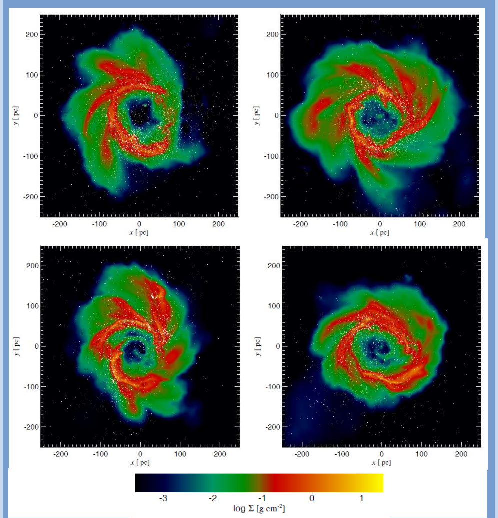


Figure 1. Projected gas density in four simulations with stochastically different initial conditions at t = 6 Myr after the start of the simulation. White dots are star particles.

The morphologies differ significantly, with different numbers, positions and sizes of star-forming clumps. However the integrated properties – size and mass of the ring, total star formation rate – are rather uniform. This shows that certain effects of AGN activity can be robustly simulated, but multiple, stochastically different, simulations are required to understand which results are robust.

Resolution

(Bourne, Zubovas & Nayakshin 2015, MNRAS, arXiv: 1507.08283)

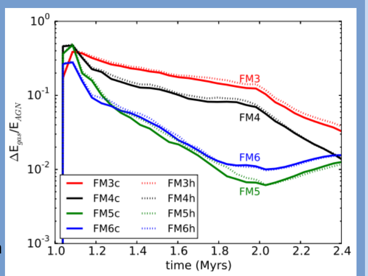
Cosmological and galaxy evolution simulations tend to have rather low resolution, with SPH particle masses $m_{SPH} > 10^5\ M_{Sun}$ [2]. This may cause certain small-scale processes to remain unresolved. We decided to test the importance of numerical resolution upon the properties of AGN feedback bubble evolution.

We ran a set of SPHS simulations [3] of AGN wind inflating a bubble in a turbulent 1-kpc-size spherical shell. The simulations probed resolutions from 10^3 to 10^6 particles (corresponding to particle masses from 10^6 to $10^3\ M_{Sun}$). The turbulent structure develops for 1 Myr unperturbed and then the AGN turns on for 1 Myr.

The results show that at low resolutions, AGN feedback does not compress gas to such high densities as in simulations with higher resolution. As a result, the gas retains much more of the input energy (see Figure 2a below) and is pushed away very efficiently (see Figure 2b below). Moreover, simultaneous radial gas inflows and outflows do not occur in low-resolution simulations.

All these results show that numerical resolution is important not just for quantitative, but also for qualitative understanding of the evolution of AGN outflows.

Figure 2a (right). Gas energy change as fraction of AGN input energy in AGN feedback simulations at resolutions from 10^3 (red) to 10^6 (blue) particles in the central kpc.



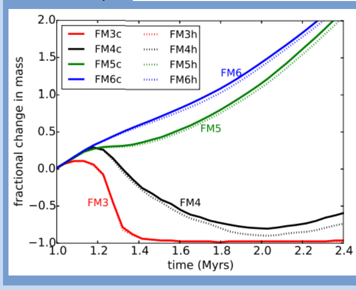


Figure 2b (left). Fractional gas mass change in the central 200 pc in AGN feedback simulations at resolutions from 10^3 (red) to 10^6 (blue) particles in the central kpc.

Feedback prescription

(Zubovas, Bourne & Nayakshin 2015, MNRAS, submitted)

The way that AGN feedback is injected into the surrounding gas also has a significant effect on the evolution of the resulting outflow. We show this with a set of simulations exploring two methods of feedback injection: "virtual" tracer particles that carry momentum and energy radially away from the AGN [4] and directly adding thermal and kinetic energy to the gas surrounding the AGN, as is usually done in cosmological simulations [5]. In addition, we explore two injection geometries: spherically symmetric and conical, where feedback is injected into a bicone with a 45º opening angle.

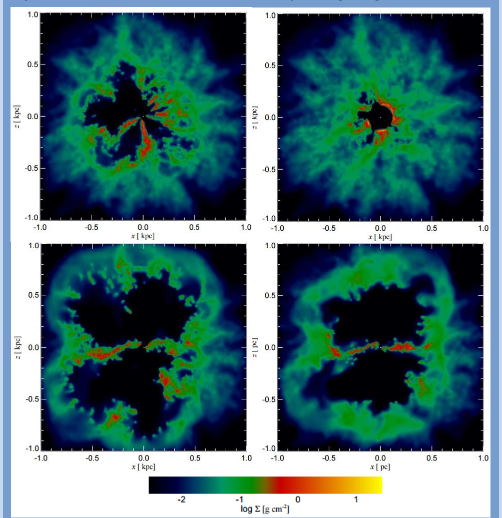


Figure 3. Projected gas density 0.5 Myr after the AGN switches on. Feedback is injected spherically (top) or conically (bottom) with virtual particles (left) or as thermal and kinetic energy (right).

Spherical injection of thermal and kinetic energy produces spherical bubbles and forces gas to accumulate at their edges, leading to unrealistic morphologies. The virtual particle model produces much more complex outflow behaviour, but is computationally expensive. A conical feedback injection geometry solves some of the issues that spherical injection has without requiring more complex simulations. This simple upgrade can significantly improve the realism of large-scale simulations with AGN feedback.

Summary and recommendations

The simulations presented above reveal several key shortcomings of large-scale numerical simulations of AGN feedback: the lack of accounting for stochastic effects, low resolution causing certain processes to be missed, and results depending qualitatively upon the subgrid prescription of feedback energy injection. Fortunately, there are ways to mitigate or even completely eliminate these issues:

- **Controlled randomness:** Stochastic processes can be identified by repeating a simulation with almost the same initial conditions, only introducing stochastic variations in particle numbers or grid placement. The similarities and differences in simulation results will show which results are robust against stochastic variations and how much variability is caused by stochastic processes.
- **Resolution advances:** Gradual improvement of resolution will lead to progressively more processes being probed in detail and their contribution to the large-scale evolution of the galaxy understood.
- **Closing the gap:** Smaller scale simulations will allow us to constrain the effects of various complex processes, such as the interaction between AGN winds and the surrounding gas, on small and intermediate scales. These results can then be used to improve current subgrid prescriptions used in large-scale simulations, bringing them into closer agreement with small-scale ones and with real systems

Together, these approaches will help interpret the Athena observations of AGN feedback in a thorough way, making use of the unprecedented resolution and detail that the observatory will provide.

References

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