Co-Evolution of Central Black Holes and Galaxies
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Growing Supermassive Black Holes Inside Cosmological Simulations

Robyn Levine[1], Nickolay Y. Gnedin[2], and Andrew J. S. Hamilton[3]

[1]Canadian Institute for Theoretical Astrophysics, Toronto, ON M5S 3H8, Canada
[2]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3]University of Colorado, Boulder, CO 80309, USA

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Using a hydrodynamic adaptive mesh refinement code, we simulate the growth and evolution of a typical disk galaxy hosting a supermassive black hole (SMBH) within a cosmological volume. The simulation covers a dynamical range of 10 million, which allows us to study the transport of matter and angular momentum from super-galactic scales down to the outer edge of the accretion disk around the SMBH. A dynamically interesting circumnuclear disk develops in the central few hundred parsecs of the simulated galaxy, through which gas is stochastically transported to the central black hole.

We have run simulations using the adaptive refinement tree (ART) code (Kravtsov *et al.* 2002 and references therein). The code follows gas hydrodynamics on an adaptive mesh, and includes dark matter and stellar particles and gas cooling. Using a "zoom-in" technique described in detail by Levine *et al.* (2008), the simulations follow the evolution of the central ~ 100 pc of a disk galaxy (measured from the location of a $3 \times 10^7\, M_\odot$ black hole particle) with a maximum resolution of 0.03 pc for 1–2 million years.

A cold, rotationally supported, self-gravitating gas disk develops in the circumnuclear region of the galaxy in each simulation (inside ~ 100 pc), with a steep power-law density distribution. The disk is globally unstable, leading to the development of waves and instabilities that drive turbulence on a range of scales, injecting energy through shocks. The turbulence is highly supersonic, effectively raising the Toomre Q-parameter and preventing the circumnuclear disk from fragmenting entirely into star-forming clumps on a free-fall time. During the zoom-in simulation, the disk shows transient features caused by spiral waves and global instabilities, which slowly allow angular momentum transport, driving gas toward the center of the galaxy.

The interior gas mass on a given scale can vary significantly so that a characteristic accretion rate is not straightforwardly determined by any one individual snapshot of the circumnuclear region. A Fourier transform of the interior gas mass indicates that the mass flux into and out of a given region is independent of timescale, i.e., accretion is a stochastic process (in the absence of events such as mergers or AGN feedback).

Over the duration of the fiducial run, there are two sudden changes in the direction of the angular momentum vector of the gas by more than 100° each. The flips are caused by individual clumps of gas with masses comparable to that of the black hole particle, which form in the disk and either fall into the center or gravitationally interact with the gas on parsec scales. Similar angular momentum flips occur in other runs containing varying black hole masses. The behavior of the angular momentum vector, particularly on small scales in the simulations, consistently shows that the gas delivered to the SMBH may have varying angular momentum, which can shift suddenly as massive clumps of gas develop and move through the disk.

References

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