Supermassive Black Hole Fueling in Cosmological Simulations

Robyn Levine*, Nick Gnedin† and Andrew Hamilton**

*CITA, 60 St. George St., Toronto, ON, M6G 1A6, Canada
†Particle Astrophysics Center, Fermilab, Batavia, IL 60510, USA
**JILA, University of Colorado, Boulder, CO 80309, USA

Abstract. 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 allowing us to study the transport of matter and angular momentum from super-galactic scales all the way down to the outer edge of the accretion disk around the SMBH. A dynamically interesting circumnuclear disk develops in the central few hundred pc of the simulated galaxy, through which gas is stochastically transported to the central black hole. We will discuss the structure and dynamics of the circumnuclear disk, and some implications for SMBH fueling

Keywords: galaxies: evolution—galaxies: high-redshift—galaxies: nuclei
PACS: 98.62.Js

1. INTRODUCTION

Active galactic nuclei (AGN) undoubtedly are an important piece of the puzzle of galaxy and cluster evolution. Since AGN are driven by accretion onto SMBHs, it is essential to understand black hole fueling. Fueling may occur continuously, over the course of some large-scale dynamical instability in the galaxy, or it may be an intermittent process, dependent entirely on the dynamics on small scales. Intermittent accretion episodes, consisting of infalling clouds of gas with randomly oriented angular momentum vectors, may contribute to the spin-down of SMBHs, thus lowering their radiative efficiency and allowing them to grow faster [e.g. 1, 2]. Therefore, modeling accretion necessitates understanding how angular momentum is distributed throughout the circumnuclear region over time.

Here we present recent results (in preparation) obtained using cosmological adaptive mesh refinement (AMR) simulations with a large dynamic range to study the transport of gas and angular momentum through the circumnuclear disk of a SMBH host galaxy over time. Further details of the simulations performed can be found in previous work [3, 4].

2. HIGH-RESOLUTION SIMULATIONS

We have performed simulations using the Adaptive Refinement Tree (ART) code [5–7]. The code follows gas hydrodynamics on an adaptive mesh, and includes dark matter and stellar particles (with stars forming at an observationally motivated rate), as well as

CP1201, *The Monster's Fiery Breath: Feedback in Galaxies, Groups, and Clusters*
edited by S. Heinz and E. Wilcots

gas cooling by heavy elements and dust (using rates from CLOUDY [8]). Additionally, radiative transfer and feedback and enrichment from stars are included in the pre-zoomed, cosmological portion of the simulation.

Beginning with a cosmological simulation with a maximum resolution of $\approx 50\,\mathrm{pc}$ proper at $z = 4$, the resolution is slowly increased one refinement level at a time, reaching a quasi-stationary state on each level before increasing to the next level. The final maximum resolution is $\approx 0.03\,\mathrm{pc}$, corresponding to 20 levels of refinement. After reaching the maximum resolution, a fraction of the gas in the center of the galaxy is replaced with a black hole particle of equal mass and momentum. The mass of the black hole particle does not change over the course of any of our current zoom-in simulations. After the introduction of the black hole particle, the simulation continues to evolve with the maximum resolution for several hundred thousand years.

Each simulation develops a similar structure: a cold, rotationally supported, self-gravitating gas disk develops in the circumnuclear region of the galaxy (inside $\sim 100\,\mathrm{pc}$), with a steep power-law density distribution. The disk is globally unstable, leading to the development of waves and instabilities which 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.

3. MASS AND ANGULAR MOMENTUM ACCRETION

As the globally unstable disk forms transient structures on a range of scales, the interior gas mass can vary significantly. The left panel of Figure 1 shows the amplitude of fluctuations in the gas mass interior to $10\,\mathrm{pc}$ over time for three different redshift simulations. The Figure gives an indication of the turbulent nature of the gas in the circumnuclear disk of the galaxy, and suggests 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 provides a natural characterization of the mass fluctuations and their dependence (if any) on time-scale. We have used the Lomb-normalized periodogram [9, 10], P_{N}, to estimate the Fourier transform of the interior gas mass, and subsequently the mass flux as a function of angular frequency, ω. The Fourier transform of the mass follows a power-law with slope ≈ -1 in each of the simulations, showing no substantial departure down to frequencies comparable to the rotational period of the disk. The time derivative of the Fourier transform gives a characteristic "accretion rate" through radius r as a function of frequency,

$$\dot{M}(\omega) = i\omega M(\omega) \approx i\omega\sqrt{\frac{P_{\mathrm{N}}\sigma_{\mathrm{M}}^2}{N}}. \tag{1}$$

Equation 1 gives an estimate of the typical mass flux of gas flowing into and out of a given region on a time-scale $2\pi/\omega$. The absolute value of the flux given by

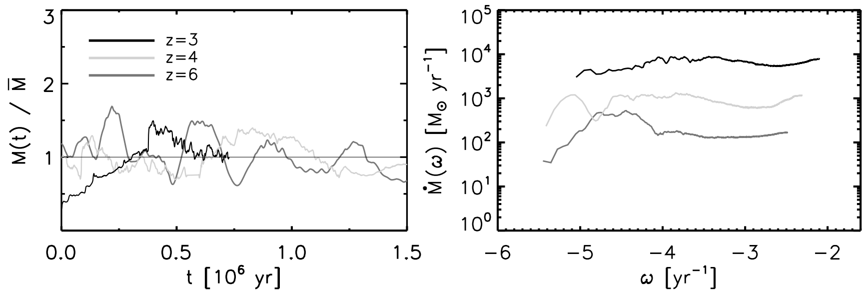

FIGURE 1. *Left:* Amplitude of fluctuations in the gas mass interior to 10 pc over time for three different redshift simulations; *Right:* Mass flux (as described in the text) as a function of angular frequency for three different redshift simulations, at 10 pc.

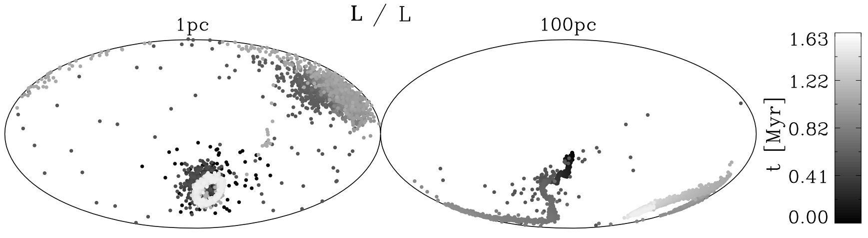

FIGURE 2. Map showing the direction of the normalized angular momentum vector, $\mathbf{L}/L$, as it changes over time in the $z = 4$ simulation. Colors correspond to the elapsed time since the introduction of the black hole particle. The maps are aligned with the mean rotation axis of the galactic disk at 1 kpc in the center.

Equation 1 is shown as a function of frequency in the right panel of Figure 1. The data are smoothed over several neighboring points (the number of points is proportional to angular frequency, ω) to reduce the noise so that the different curves are readily distinguishable.

The mass flux follows the same stochastic behavior at different epochs, as well as for different black hole masses (not shown here). The fluctuations do not appear to be correlated with the orbital period at any radius in the circumnuclear disk. The flat slope of the flux, $\dot{M}(\omega)$, shows that the rate of transport is independent of frequency, i.e. that accretion is a stochastic process with no preferred time-scale.

The angular momentum of gas that is stochastically accreted may ultimately help determine the accretion efficiency of the black hole, and possibly the mode of feedback it produces [e.g. 1, 2, 11, 12]. Our simulations model gas on parsec scales, enabling us to resolve the direction of the angular momentum vector of gas (measuring the position and velocity relative to that of the black hole particle) as it evolves over time.

Figure 2 shows a map projection of the direction of the normalized angular momentum vector, $\mathbf{L}/L$, as it evolves at 1 and 100 pc from the black hole particle (for the $z = 4$ simulation). The maps are oriented with the angular momentum of the disk on kiloparsec scales in the center. The disk is slightly warped in the circumnuclear region, so that the axis of the disk is oriented at an angle to the large-scale disk.

At 1 pc, the direction of the angular momentum vector starts out at approximately the same orientation as the larger scales, but shows slightly more scatter. The map shows two sudden changes in the direction of the angular momentum vector by $\gtrsim 100^\circ$ each. The first incident, at $t \approx 0.55$ Myr, occurs as a clump of gas with mass comparable to that of the black hole falls into the center. The scatter in the measurement of the angular momentum vector near this time (visible at 100 pc as well) corresponds to a temporary displacement of the black hole particle as the clump reaches the center. The second incident, at ~ 1.2 Myr, is the result of gravitational interaction with a massive clump of gas which develops at > 100 pc and continues to move toward the center of the disk at late times. Similar angular momentum flips occur over the course of several other runs with varying black hole masses.

At 100 pc, the angular momentum vector slowly changes direction, showing little scatter over the course of the simulation. The slow change in direction at 100 pc may correspond to the increased warping of the disc as the simulation progresses. 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.

ACKNOWLEDGMENTS

Thanks to the SOC and LOC for a very stimulating and well-organized meeting! This work was supported in part by the DOE and the NASA grant NAG 5-10842 at Fermilab and by the NSF grants AST-0134373, AST-0507596, and AST-0708607. Simulations were run on the IBM P690 array at the NCSA and SDSC (under grant AST-020018N), as well as on the Joint Fermilab-KICP Supercomputing Cluster (supported by grants from Fermilab, the KICP, and the University of Chicago)

REFERENCES

1. A. R. King, and J. E. Pringle, *MNRAS* **377**, L25–L28 (2007).
2. A. R. King, J. E. Pringle, and J. A. Hofmann, *MNRAS* **385**, 1621–1627 (2008), `arXiv:0801.1564`.
3. R. Levine, N. Y. Gnedin, A. J. S. Hamilton, and A. V. Kravtsov, *ApJ* **678**, 154–167 (2008), `arXiv:0711.3478`.
4. R. Levine, *Simulating the growth of a disk galaxy and its supermassive black hole in a cosmological context*, Ph.D. thesis, University of Colorado at Boulder (2008).
5. A. V. Kravtsov, A. A. Klypin, and A. M. Khokhlov, *ApJS* **111**, 73–+ (1997), `astro-ph/9701195`.
6. A. V. Kravtsov, *High-resolution simulations of structure formation in the universe*, Ph.D. thesis, AA(NEW MEXICO STATE UNIVERSITY) (1999).
7. A. V. Kravtsov, A. Klypin, and Y. Hoffman, *ApJ* **571**, 563–575 (2002), `astro-ph/0109077`.
8. G. J. Ferland, K. T. Korista, D. A. Verner, J. W. Ferguson, J. B. Kingdon, and E. M. Verner, *PASP* **110**, 761–778 (1998).
9. N. R. Lomb, *Ap&SS* **39**, 447–462 (1976).
10. W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical recipes in C. The art of scientific computing*, Cambridge: University Press, |c1992, 2nd ed., 1992.
11. M. Volonteri, M. Sikora, and J.-P. Lasota, *ApJ* **667**, 704–713 (2007), `0706.3900`.
12. E. Berti, and M. Volonteri, *ApJ* **684**, 822–828 (2008), `0802.0025`.