



A Particular Appetite: Cosmological Hydrodynamic Simulations of Preferential Accretion in the Supermassive Black Holes of Milky Way Size Galaxies

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ABSTRACT

[IAU Abstract as Placeholder] Using cosmological hydrodynamic simulations of Milky Way-type Galaxies, we explore the effect of accreted gas as feeding mechanisms for supermassive black holes. By examining two of these galaxies with differing merger histories, one characterized by several major mergers and the other with a quiescent history, we can examine the importance of merger history on black hole accretion. This study is an extension of Bellovary et. al. 2013, which did a similar study analyzing the accretion of high mass, high redshift galaxies and their central black holes. Bellovary found that the gas accreted by the central black holes was proportional to that accreted by the host galaxy. Contrary to the previous study’s results, we’ve found that while a galaxy with a quiescent history will still have a black hole mirroring the accretion of its host, a galaxy with an active merger history has a central black hole that is preferentially fueled by gas accreted through mergers. We look to the the angular momentum of the accreted gas in these Milky Way analogs to develop a clearer picture of the mechanisms best fueling their central SMBHs.

Subject headings: Black hole physics – Galaxies: spiral – Galaxies: kinematics and dynamics – Methods: Numerical – Others?

1. Introduction

Supermassive black holes (SMBHs) are thought to exist in almost all massive galaxies. These black holes become active galactic nuclei (AGN) during periods of high accretion and wane in periods of quiescence. (?) The galaxy’s size, metallicity, and other environmental effects may help to influence the growth of the black hole residing at its center; however, little is known about the relationship between these SMBHs and their much larger host galaxies, as well as how they grow and evolve together.

*In following P: M-bulge mass, M-bulge luminosity. [Ho review]2

The $M-\sigma$ relation, which relates the SMBH’s mass and the velocity dispersion of the host galaxy’s central stellar population, gives some insight into the complex interplay between these objects. ? A prominent trend appears, as SMBHs tend to scale with their spheroidal center of their host galaxies, i.e. less massive SMBH residing in galaxies with less disperse bulges, and more massive SMBH living in galaxies with larger velocity dispersions in their bulges. The tightness of the relation is significant and can be seen over several orders of magnitudes in velocity dispersion and black holes mass. (Two in sigma, 4 in mass) Increased scatter exists in the region of very high mass galaxies and among the low mass galaxies. However, scatter in less massive galaxies may imply that there are several channels of black hole growth at play in the low mass end of the relation. One standard explanation for the $M-\sigma$ relation lies in galaxy mergers, which build up galaxies, feed SMBHs, and assemble bulges. These large, active mergers are thought to create feedback from the SMBH which affects the overarching structure of the galaxy.

Major mergers between massive galaxies are thought to be efficient fueling mechanisms for bright AGN. The large influx of material due to tidal torques from the merger collects into pockets of gas and dust which cause bursts of star formation and helps funnel gas

directly into the center where the SMBH resides. (Hopkins 04, Richards 06, Reddy 08) Additionally, the most massive, highest-luminosity AGN (i.e. quasars) tend to reside in incredibly luminous infrared galaxies where star formation is abundant, signifying that major mergers may have recently occurred. Distorted morphologies are often characteristics of quasar hosts, and companions can also be present around quasars, both of which are evidence that strengthen the possibility of a recent merger having affected their lifetimes.

In many less massive AGN, however, there is a clear lack of distorted morphologies, close neighbors, and/or other obvious merger evidence. Ryan 2007 (Seyfert 1, smaller than MWG), Hicks 2013 (Seyfert and quiescent galaxies) It is also important to note that many of these AGN exist in spiral galaxies, which are unlikely to have been recently disturbed by major mergers. (**Schawinski 2011**) Nevertheless, some evidence suggest (Governato 2009) some disturbed galaxies may reform a disk quickly, even if their history is characterized by many mergers. More recently, Triester (2012) has suggested that only the highest luminosity AGN require fueling via major mergers, an effect which seems to scale with luminosity rather than redshift. They found that 90% of AGN across all redshifts are fueled by various other mechanisms which may include minor mergers, flybys, and smooth accretion, whereby gas is directly accreted via large filaments from the ambient intergalactic medium. Secular processes, including bar formation and disk instabilities, may also be prominent forms of accretion for these SMBHs.

Smooth accretion, via filamentary inflows, seems a likely candidate for fueling these undisturbed galaxies. The cold flow filaments that feed these galaxies are dependent on the galaxy’s mass. Smoothly accreted gas will fuel through cold flow filaments until the galaxy halo reaches a mass near $10^{11} M_{\odot}$. Once the galaxy is greater than this mass threshold, the

gas will reach the virial radius of the halo and the rapid increase in temperature within the radius causes the gas to be shocked as its temperature quickly increases. Fueling mechanisms are seen to vary across galaxies of different masses based on the diversity of their history and appearance, such as through the major and minor mergers and secular processes described above. Here, we will discuss the fueling mechanisms which also vary between galaxies of similar mass due to different merger and formation histories.

In this paper, we discuss the gas accretion history within two galaxy simulations that appear similar at $z = 0$ but have very different merger histories. Our "active" galaxy, h258, has a history characterized by many major mergers, while our "quiet" galaxy, h277, has a quiescent history dominated by cold flow accretion and few minor mergers. These galaxies look quite similar at $z=0$, and have many of the same properties as the Milky Way including M_{vir} (mass within the virial radius), stellar mass, and v_{circ} (circular velocity). However, without a deeper examination, we might not realize they have such varying merger histories. Milky Way-type galaxies host SMBHs on the order of $10^6 M_\odot$, which are likely the most common type of massive black hole, yet little is known about them or how they may grow. By examining the feeding mechanisms of these galaxies, as well as what type of gas feeds their central SMBHs, we will be able to compare the accretion rates between h258 and h277 to determine which accretion methods dominate within the central regions of these Milky Way-size galaxies.

Bellovary et. al. (2013) ? compared simulations of three high mass, high redshift galaxies and found that while mergers and smooth accretion both build up galaxies, no particular method was more adept at feeding the SMBH at their centers. Using a similar method as Bellovary et. al. (2013), this work compares the fueling mechanisms between

two MW mass galaxies and the accretion affecting each of their SMBHs. We will compare the BH fractions and halo fractions between and within the galaxies to look for clues about SMBH preferential feeding within these MW-size galaxies and how their histories lead to galaxies with such similar structure.

2. Simulation Parameters

2.1. Low Resolution GASOLINE Simulations

The cosmological simulations have been run using the smoothed particle hydrodynamics (SPH) N-body tree code Gasoline (**Stadel 2001; Wadsley 2004**). (?) Prescriptions for star formation, supernova feedback (**Stinson 2006**), metal diffusion (**Shen 2010**), and MBH formation, feedback, and accretion (**Bellovary 2010**) are included within Gasoline. Each simulations assumes a WMAP cosmological model (Spergel 2007), Kroupa initial mass function (Kroupa 2001), and a uniformly distributed ultraviolet background (Haardt & Madau 1996). Gasoline simulated galaxies are shown to lie conform with the observed Tully-Fisher relation (Governato 2009), the size-luminosity relation (Brooks 2011), and the mass-metallicity relation (Brooks 2007), in addition to having realistic matter distributions and baryon fractions (Governato 2010; Guedes 2011). Primordial cooling and a low-temperature extension to the cooling curve is used to trace metals (Bromm2001). Gas is allowed to reach a minimum temperature of 100 K, though cooling via molecular hydrogen or metals is not included. The aforementioned works have previously demonstrated that realistic galaxy models can be obtained without the use of these advanced features. (Christensen2012, in addition). Though these previous works have not included AGN feedback or its effects, for small to moderate mass galaxies (like those of previous and current studies) our research shows their central supermassive black holes have little affect

on the global properties of their hosts and only directly impacts the central region of their galaxy. Therefore, we are confident these simulations are in good accordance with the broad range of properties in current galaxy observations.

We have examined two simulations, each of a uniform volume cube with 50 Mpc sides. [Volume normalization technique?] The main halo of each simulation results in a Milky Way-size spiral galaxies with $z=0$ masses between $6\text{--}8 \times 10^{11} M_{\odot}$. The simulations each have a force resolution of 300 pc [Note: I have 300 written in my research notebook, but B13 says 260. The notes I have are the ones I took so AAS so maybe that's a rounded up value?]. The gas, dark matter, and star particles have masses of $2 \times 10^5 M_{\odot}$, $3 \times 10^5 M_{\odot}$, and $7 \times 10^4 M_{\odot}$, respectively. [Your paper includes a table of simulation properties. Should I create one as well? I feel like yes.]

The simulation includes stochastically modeled star formation, including a density threshold (2.5 amu cm^{-3}) for gas particles above which they become eligible to form stars; the gas must also be below a temperature threshold of 10^4 K . Additionally, we utilize a star formation efficiency parameter of $c^* = 0.1$. Our supernova feedback energy is $E_S N = 1 \times 10^{51} \text{ erg}$ and, using the blastwave equations from McKee & Ostriker (1977), the energy is passed to surrounding particles within a calculated radius. The equation also determine how long the cooling is shut off for heated particles. These parameters and resolution choice allow the galaxies to adhere to the stellar-mass-halo-mass relation at $z=0$ and maintain a realistic period of star formation. (Moster 2010; Munshi 2013) We are confident with these criteria and restraints that we reasonably represent growth in the galaxy and its SMBH. [Note: I did change the variables to $h258/h277$ values. C_{star} is the same, but E_{sn} was larger.]

Like the star formation, seed black hole formation is modeled stochastically but requires the additional stipulation that black holes must form from zero-metallicity gas. A gas particle that has zero-metallicity and also meets the requirements for star formation will have a probability, χ_{seed} , that it will become a black hole. The resulting black hole will maintain the same mass as its parent gas particle (2×10^5) M_{\odot} . We set $\chi_{seed} = 0.1$ to achieve adequate MBH occupation fractions, without an over production of merger events between MBHs. This circumvents the Soltan arguments wherein mergers alone feed MBHs almost entirely without allowing for accretion growth. This method is nearly consistent the theories of direct collapse black holes from gas (Couchmann & Rees 1986, Abel 2002, Bromm & Larson 2004) and Population III star black hole formation (Loeb & Rasio 1994, Eiseinstein & Loeb 1995, Koushiappas 2004, Begelman 2006, Lodato & Natarajan 2006). Utilizing this requirement, we ensure that black hole formation ceases at high redshift, since at this time the interstellar medium (ISM) has become overwhelmed with metals due to supernova remnants. Black holes are not fixed within their host, allowing them to be dynamically affected by mergers and other perturbations within the galaxy. Multiples may also form within the same halo. Dark matter particles have slightly larger masses than black holes to tamper the effects of artificial tow-body scattering and to keep the black holes in the center of their dark matter host particles. Bellovary et. al. 2011 expands on the details of seed black hole formation. [Put in these details?]

Black hole mergers can occur when they meet two criteria. First, the black holes must be within twice the softening length of each, and they must also satisfy $(1/2)\delta v^2 < \delta a \cdot \delta r$, where δv and δa are the velocity and acceleration differences between the two black holes and δr is the distance separating them. In addition to gaining mass via merger, black holes may also accrete gas via the Bondi-Hoyle method:

$$\dot{M} = \frac{4\pi\alpha G^2 M_{BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}, \quad (1)$$

where α is a constant of 1, ρ is the density of the surrounding gas, c_s is the sound speed, and v is the black hole’s relative velocity compared to the gas. In response to the accretion of gas, feedback energy is released onto the surrounding gas:

$$\dot{E} = \epsilon_r \epsilon_f \dot{M} c^2 \quad (2)$$

which is proportional to the accretion rate of gas and assumes $\epsilon_r = 0.1$ and $\epsilon_f = 0.03$ for the radiative efficiency. The efficiency $\epsilon_f = 0.03$ is where the feedback energy couples to gas, ”which is distributed over the SPH kernel as thermal energy to the 32” nearest gas particles. [Look into this. Confused.] Though other groups (such as Sijacki, 2007, Di Matteo 2008) use a higher value for this efficiency, $\epsilon_f = 0.05$, we’ve found this increased efficiency overpowers the feedback and highly limits gas accretion. Using $\epsilon_f = 0.03$, the MBHs are in better agreement with the MBH-host galaxy scaling relations, e.g. $M_{BH}-\sigma$ and $M_{BH}-M_{bulge}$. This efficiency value is a simulation parameter used in subgrid feedback models, but does not represent a specific physical quantity, and therefore some variation among codes is expected. Finally, as this work’s main concern is the relative accumulation of gas through various accretion methods and not the total value of accreted gas mass, these results are not highly sensitive to adjustments in the feedback implementation.

2.2. High Resolution CHANGA Simulations

Charm N-body GrAvity solver, ChaNGa, was used to run the second iteration of these N-body + SPH galaxy simulations. An initial DM-only, uniform resolution 50 comoving Mpc box was used to determine which halos would be selected for zoom-in examination, including the two halos examined in this paper. The DM-only simulation assumed a WMAP Year 3 cosmology (Spergel 2007) with the following specifications: $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, $H_0 = 73$ km/s, and $\sigma_8 = 0.77$. The halos h258 and h277 were chosen for their Milky

Way-mass at $z=0$ and their active and quiescent merger histories, respectively. The halos have virial masses defined relative to a critical density, ρ_c , where $\rho/\rho_c = 100$ (Gross 1997) where h258 and h277 have virial masses of $M_{vir} = 7 \times 10^{11} M_\odot$ and $M_{vir} = 8 \times 10^{11} M_\odot$, respectively. A recent binary merger characterizes the h258 halo at $z=1$, while h277 has its last major merger near $z \sim 3$. A second "zoom-in" high resolution simulation was run for both of these galaxies including gas and star particles using the volume renormalization of Katz & White 1993. This technique retains the large volume simulation size at lower resolution while allowing for only the closest few virial radii from the primary halo to be simulated at the highest resolution. By keeping the largest volumes at low resolution, we are able to account for building of angular momentum through the large scale tidal field in tidal torque theory. These high resolution simulations were run from $z=150$ to $z=0$.

Both N-body+SPH volume renormalized simulations of h258 and h277 have been previously examined in other publications. Governato et. al. 2009 studied the regrowth of the large disk structure in h258 by $z=0$ when such a recent merger affects the galaxy. However, the results from Governato 2009 were based upon the previous Gasoline results described above. The results of this paper, both from Gasoline and ChaNGa, utilize the same initial conditions but the latter is simulated at a high resolution allowing the following new physics to be included: • spline force softening lengths of 174 pc • dark matter particles with masses of $1.3 \times 10^5 M_\odot$ • initial gas particle masses of $2.7 \times 10^4 M_\odot$ • star particles are created with 30% of their parent gas particle mass; therefore, a maximum initial mass of $8100 M_\odot$ • star particles may lose mass through SNe and stellar winds • each galaxy contains about 5 million DM particles inside the virial radius at $z=0$ • each galaxy contains over 14 million DM, star, and gas particles total.

The resolution of both force and mass in these simulations is comparable to the "Eris" simulation which has one of the highest resolutions for an N-body+SPH cosmological

simulation of a Milky Way-mass galaxy so far produced. While cooling physics and energy feedback from supernova are included in the same way as previous Gasoline simulations, these ChaNGa simulations also take into account metal line cooling and H_2 . The high resolution of the simulations allow for resolving the high density regions where star formation occurs at $\rho = 100 \text{ amu}/\text{cm}^3$ and adjusting the gas cooling and stellar formation prescriptions. By including metal line cooling, more gas is allowed to cool and fuel star formation within the central regions of the galaxy. (Christensen et al. 2011) The new simulations also allow star formation to be directly affected by nearby H_2 abundances. This abundance is regulated by the gas’s ability to self shield and its metallicity, characteristics in keeping with observational results. (Leroy 2008, Bigiel 2008, Blanc 2009, Bigiel 2010, Schrubba 2011) The H_2 prescription includes gas-phase and dust grain formation, as well as H_2 destruction via Lyman-Werner radiation due to nearby stars. Prior to implementing the H_2 model, gas particles needed to reach a density threshold while remaining below a set temperature ($T < 1000 \text{ K}$) before star formation could occur. Utilizing the H_2 prescription removes the need for a density threshold as high densities ensuring stars only form in high density regions. For more details on the H_2 prescription, see Christensen et. al. 2012.

Primordial and metal-line cooling are described in Shen et. al. 2010, and also takes into account the diffusion of metals mixing in the interstellar medium. At $z=9$, a uniform UV background is applied to simulate the cosmic reionization energy in a variation of Haardt & Madau 2001. Star particles form along the Kroupa initial mass function (Kroupa 1993). Supernova feedback releases 10^{51} ergs of thermal energy and affects a ”blastwave” radius determined by the method of Ostriker & McKee 1988. In the affected region, cooling turns off for a time relative to the expansion phase of the SN remnant. SN Ia and II from Thielemann 1986 and Woosley & Weaver are adopted, respectively, and implemented through the method of Raiteri 1996. Both supernova ”blastwave” radius calculations and supernova (Ia and II) prescriptions are as described in detail by Stinson 2006. These

methods have proven to adhere to the observed, redshift dependent stellar mass-metallicity relation for galaxies. (Brooks 2007; Maiolino 2008)

In this paper, we [demonstrate that these high resolution ChaNGa simulations have mirroring results to their low resolution Gasoline simulations. This second wave analysis allows us to feel confident in our results as we describe the varying accretion preferences for these simulated Milky Way-mass galaxies, h258 and h277.

3. Reduction Method

In this analysis, we use the method utilized in Brooks et. al. (2009) to trace gas particles from their origin, through their journey into the galaxy, and determine their position within the SMBH or its host. Brooks et. al. (2009) studied the accretion of gas by galaxies in cosmological simulations with a focus on gaseous and stellar buildup of their disks. We use this method to trace the gas particles from their initial location to their moment of halo entry and, for some of the particles, into the SMBH.

As we discussed in the introduction, there are a variety of fueling mechanisms thought to grow SMBH. Even among galaxies of similar mass, different evolutionary pathways and merger histories can lead to different mechanisms of SMBH accretion. Gas particles are initially traced prior to their accretion onto the main halo to determine whether they occupied a different halo at their formation. The particles are then classified by their method of entrance into the primary halo. If the gas particles existed in the primary halo at the first time step ($z=4$ in this study), they are classified as "early" gas. The final fraction of "early" gas in the galaxy at $z=0$ is less than four percent for both h258 and h277, a negligible amount. Gas that belonged to a different halo than the primary prior to

accretion is classified as "clumpy" and enters the primary halo through mergers.

The Amiga Halo Finder identifies all of the galaxies in the simulations by identifying the virial radii of the halos based on an overdensity using the criterion for a flat universe. (Bellovary 2013) We select the primary halo by determining the most massive galaxy at $z=0$ and locating the central SMBH. We then trace the SMBH back through time, determining its host halo in each snapshot. Gas particles that are part of merger events are traced back through every merger they've encountered—within their merger trees—to determine their origin and which other halos each gas particles previously inhabited (Too anthropomorphic?).

All other gas is classified as entering the halo via "smooth" accretion, and is then subdivided into two categories: "cold" and "shocked." In the cases where a shock does not develop, cold gas will usually flow into the halo via large-scale, dark matter filaments. (Bellovary 2013) It's possible for the filaments to also be dense enough to pierce an already developed shock allowing for cold gas to funnel into the central region of the galaxy where it can accrete onto the SMBH without being heated to the virial temperature.

Gas particles that undergo smooth accretion, may shock when entering the virial radius of the galaxy, depending on the mass of the galaxy. If the galaxy halo is around or greater than $10^{11} M_{\odot}$, the gas will shock. The galaxies in this study reach final masses on the order of $10^{12} M_{\odot}$, therefore, shocked gas begins to enter the galaxy by the later timesteps of our simulation when it has reached this critical mass.

Shocked gas is defined as gas reaching virial temperature as it enters the primary halo. Therefore, we determine shocked particles through an increase in entropy and temperature

using the following criteria:

$$T_{shock} \geq 3/8 T_{vir} \quad (3)$$

where T_{vir} is the virial temperature of the halo and T_{shock} is the temperature of the gas particle, and

$$\Delta S \geq S_{shock} - S_0 \quad (4)$$

where S_0 is the initial entropy of the gas particle and

$$S_{shock} = \log_{10}[3/8 T_{vir}^{1.5}/4\rho_0] \quad (5)$$

where ρ_0 is the gas density prior to experiencing the shock.

Gas entering the halo via smooth accretion, whether cold or shocked, is traced to $0.1 R_{vir}$ from the galaxy, a distance after which the thermal status of the particle can no longer be confidently tracked, as supernova feedback can mimic virial shocking. Gas particles that reach this distance with the above increased in entropy and density are considered shocked particles, while all others are categorized as cold. (“See Brooks et. al. 2009 for complete details about shock physics.”)

Once all the gas particles have been individually categorized, we can use these labels to determine the methods of accretion onto these Milky Way-size galaxies. With the information about which particles are accreting onto the SMBH (from the gas reservoir of particles that have been accreted by the galaxy), we can better compare the methods feeding both the galaxy and its SMBH. We can then determine whether there exists a method more efficiently building up these kinds of galaxies and their SMBH..

4. Results

From the initial analysis of the low resolution Gasoline simulations, we have determined that the merger histories of these two galaxies has a pronounced effect on the resulting accretion of gas into the SMBH and its host.

4.1. Low Resolution h258

The galaxy, h258, is characterized by an active merger history including a major merger at $z=1$. Our study found that nearly 65 % of the gas accreted by the central SMBH was gas accreted via mergers, while only 39 % of the total gas accreted by the galaxies was through mergers. This results shows explicitly that a preference exists for the SMBH to accrete gas gained through mergers. This is contrary to previous results of ?. (?) found a *slight* preference for gas of a lower angular momentum to enter the SMBH By examining the angular momentum of the gas accreted onto the SMBH at the moment it enters the halo, we were able to determine that a significant preference exists for gas with lower angular momentum to enter the SMBH. The gas attained through mergers tends to enter the halo with a lower angular momentum; this may explain the SMBH’s preference for merger gas.

4.2. Low Resolution h277

Our quiescent galaxy, h277, was characterized by few mergers in its past, its final major merger occurring around $z \approx 3$. Similar to Bellovary et. al. 2013 study, which found SMBH accretion in high mass, high redshift galaxies mirror their hosts in terms of accretion, h277’s SMBH accretes a similar fraction of each type of gas, comparable to its host galaxy. So, h277, unlike the active h258, found no preference for the SMBH to prefer any one kind of gas in its accretion. Like the SMBH in the previous study, the same fraction of gas entering

the halo would then be accreted onto the SMBH. (The gas enters a sort of reservoir and enters the SMBH somewhat uniformly.) As these SMBHs are similar in size and appearance at $z=0$, this indicates that the varying histories of these simulations plays a role in the evolution of these galaxies and their central SMBH.

4.3. High Resolution h258

(Assuming high rez finds same preferential accretion?)

- Just as we found in the lower resolution simulation (Can I reference my AAS/IAU posters here?), the high resolution sees a distinct preference for accreting gas that has been gained through the many mergers in its history.
- (MAYBE. We don't know if this is true yet.)

5. Conclusion

This is a conclusion. La la la.

Thank you to the Fisk-Vanderbilt Masters-to-PhD Bridge program for their continued funding and support. [GET GRANT NUMBER]

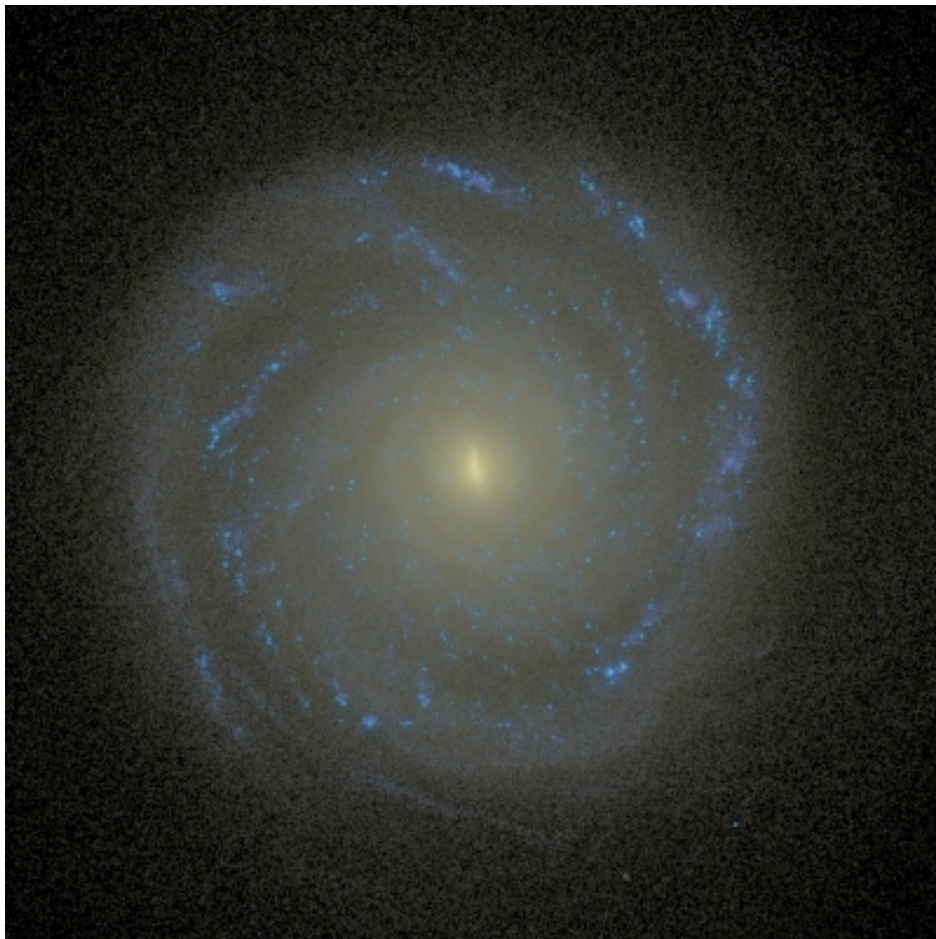


Fig. 1.— Face-on and edge-on Sunrise images of our GASOLINE galaxy, h258, which has an active, merger-rich history.

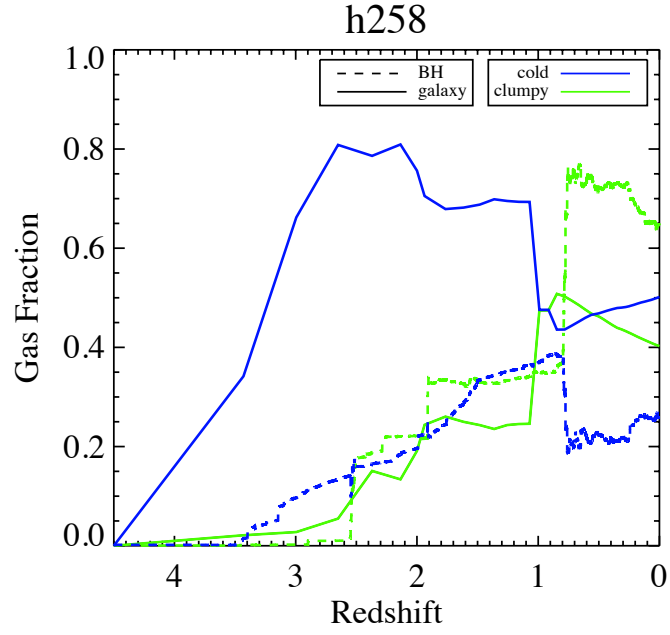


Fig. 2.— Gas fraction across redshift for galaxy (solid lines) and central BH (dashed lines). Green lines signify gas fractions accreted via mergers and blue lines designate gas accreted via cold flow.

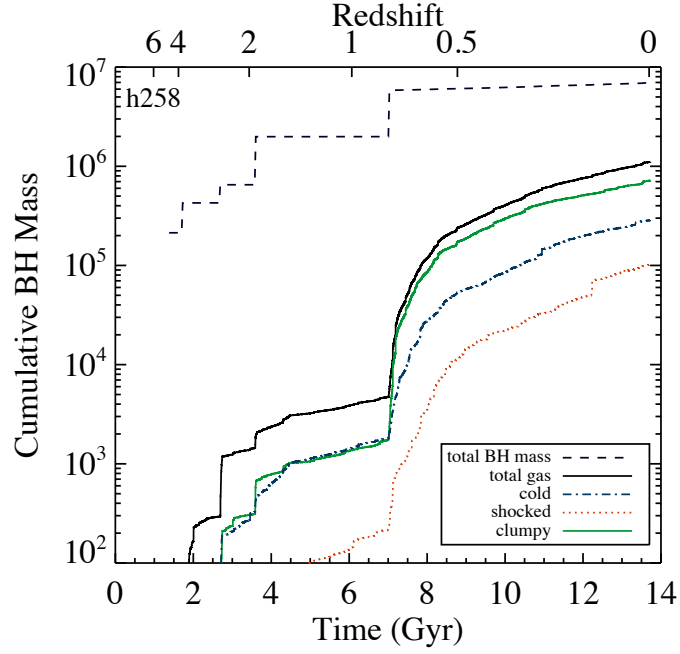
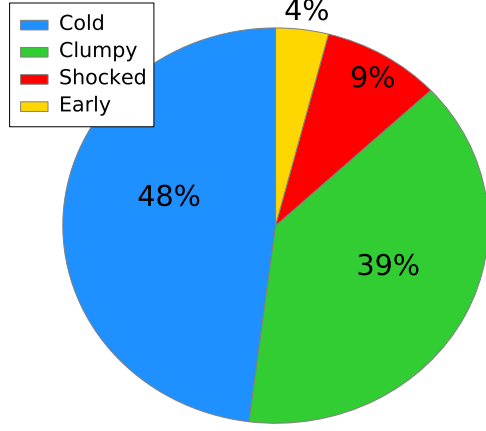
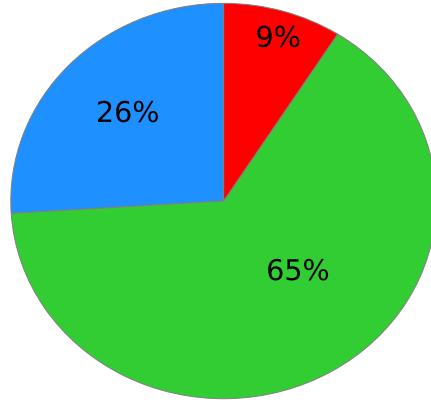


Fig. 3.— The central BHs cumulative mass as a function of time and redshift. The black dashed line indicates the total cumulative BH mass. The black solid line indicates the total gas mass. The blue dot-dashed line indicates the gas mass accreted via cold flows. The green solid line indicates the gas mass accreted through mergers. The red dashed line indicates gas mass that was shocked upon entry into the halo.



h258 Galaxy Gas Fractions



h258 Black Hole Gas Fractions

Fig. 4.— Gas fractions of the gas particles accreted in h258 by the main halo (above) and the SMBH (below), distinguished by type. Blue, green, and red distinguish gas gained through cold flows, gained through mergers, and gas shocked upon entry, respectively. Yellow indicates gas that existed within the main halo upon formation; this "early" gas is negligible ($\lesssim 1\%$) within the SMBH.

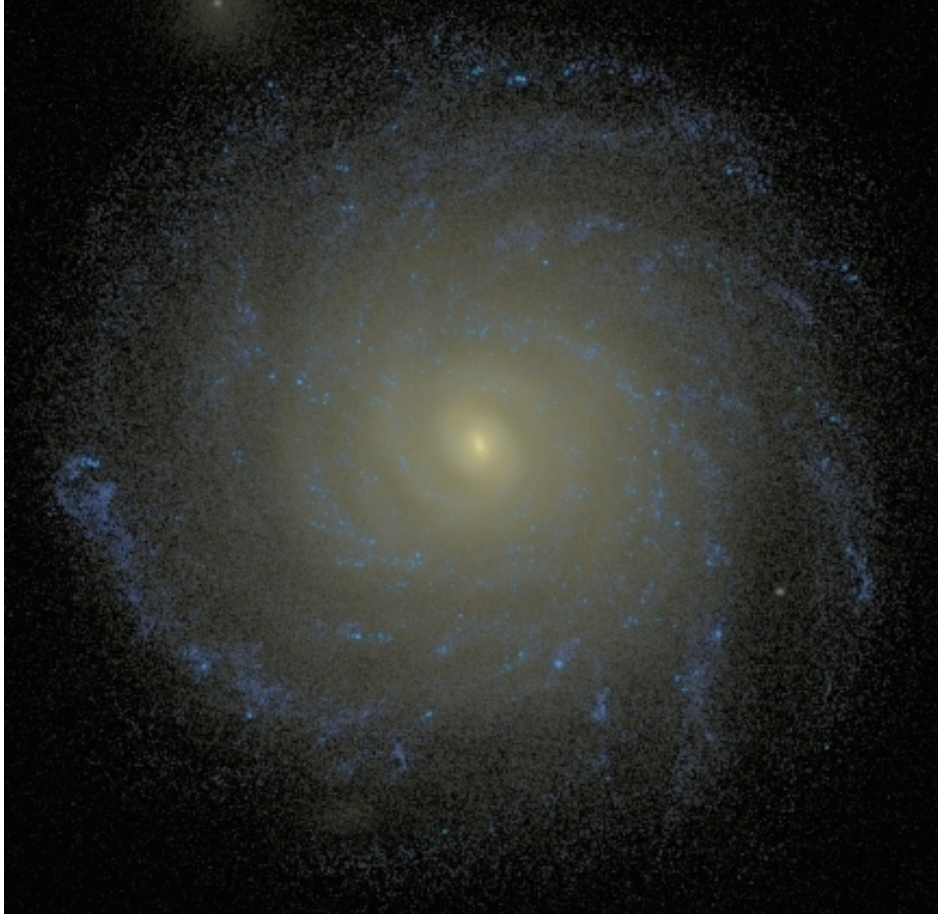


Fig. 5.— Face-on and edge-on Sunrise images of our GASOLINE galaxy, h258, which has an active, merger-rich history.

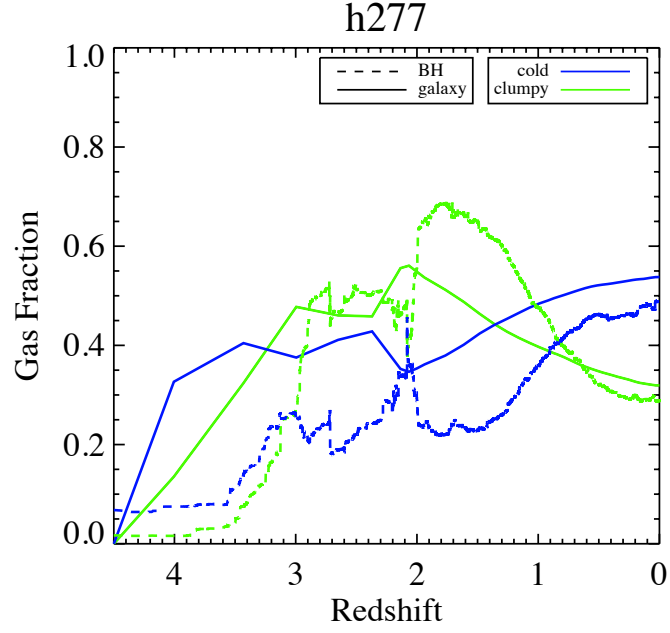
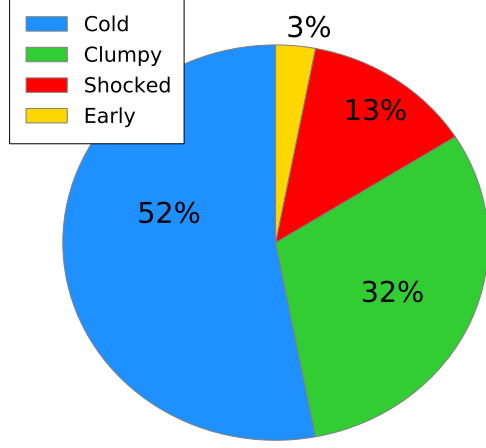
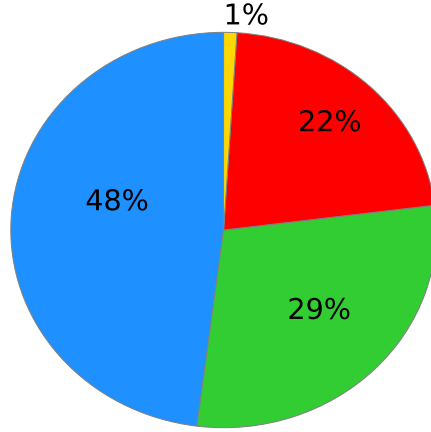


Fig. 6.— Gas fraction across redshift for galaxy (solid lines) and central BH (dashed lines). Green lines signify gas fractions accreted via mergers and blue lines designate gas accreted via cold flow.



h277 Galaxy Gas Fractions



h277 Black Hole Gas Fractions

Fig. 7.— Gas fractions of the gas particles accreted in h258 by the main halo (above) and the SMBH (below), distinguished by type. Blue, green, and red distinguish gas gained through cold flows, gained through mergers, and gas shocked upon entry, respectively. Yellow indicates gas that existed within the main halo upon formation; this ”early” gas is negligible ($\lesssim 1\%$) within the SMBH.

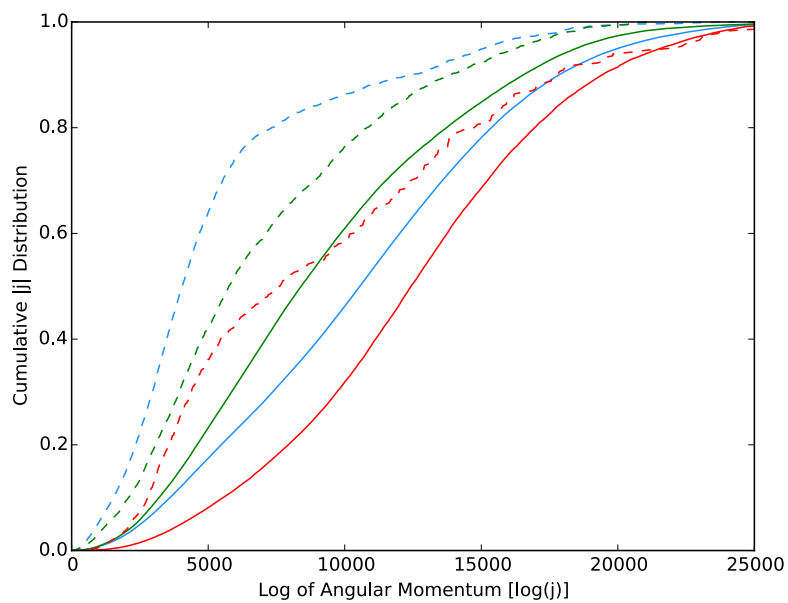


Fig. 8.— Cumulative distribution of angular momentum of the gas particles as they accrete onto the main halo (solid lines) and central black hole (dashed lines).