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Sgr A* GROWTH THROUGH HUBBLE TIME

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Abstract. We study the growth of supermassive black hole at the center of Milky Way galaxy known as Sgr A* source in a Local Group type of environment which was produced in cosmological N-body simulation known as Via Lactea II (VL-2). We use the VL-2 merger tree as a framework to test semi-analytic recipes for black hole growth that includes dynamical friction, tidal stripping, and gravitational wave recoil in over 20,000 merger tree realizations. We present a new model (PA) which is merger driven but with Prolonged gas Accretion at lower rates for the growth of $\leq 10^7$ $M_\odot$ black holes that reside at the centers of spiral and dwarf galaxies. In this model, the effects of all subgrid physics (stellar and AGN feedback, and accretion disk microphysics) are bundled into one parameter for gas accretion efficiency that can be constrained by future small-scale, fully general relativistic magnetohydrodynamic AGN simulations. With this approach, gas accretion onto the black hole is fast at high rate for $\sim$ 1:1 major mergers and prolonged at low rate for $\sim$ 10:1 major mergers. This model does not use the black hole fundamental plane or the M - σ relation to limit black hole growth and it successfully reproduces the results of the FPL models, when applied to the growth of Sgr A*.

1. INTRODUCTION

Supermassive black holes, with masses of $10^6 M_\odot \leq M \leq 10^{10} M_\odot$, are widely believed to dwell at the centers of elliptical galaxies and spiral bulges (e.g. Kormendy & Richstone 1995); the best known example is observed at the center of the Milky Way, with a mass $M_{\mathrm{SMBH}} = 4.2\times10^6\, M_\odot$ (Ghez et al. 2008). The deep connection between the evolution of SMBHs and galaxies is perhaps best encapsulated in a remarkable correlation between the SMBH mass and the velocity dispersion of the host spheroid (Gebhardt et al. 2000, Ferrarese & Merritt 2000). The dispersion in the *black hole fundamental plane* (Hopkins et al. 2007) points to an intrinsically tight correlation, at least for a sample of nearby bright spiral and elliptical galaxies with clear dynamical SMBH signatures. However, on a smaller mass scale, in systems that have a mass comparable to the Milky Way mass or smaller, central SMBHs may become less common as bulges become less common (Ferrarese et al. 2006), and in some instances they disappear entirely, such as in the case of M33 (Merritt et al. 2001, Gebhardt et al. 2001), and NGC 205 (Valluri et al. 2005). In the current picture of SMBH assembly, the black hole begins life as a low mass "seed" black hole at high redshift. The most likely candidates for SMBH seeds are the remnants that form from the first generation of stars sitting deep within dark matter halos (Madau & Rees 2001, Heger et al. 2003) – so called Population III stars.

Gas accretion is thought to play a critical role in fueling the early stages of black hole growth (Merloni 2004), and this may explain the tightness of the $M_{BH} - \sigma$ relation (Kazantzidis et al. 2005). Since high redshift galaxies are thought to be especially gas-rich, each merger brings a fresh supply of gas to the center of the galaxy, and new fuel to the growing supermassive black hole (Mihos & Hernquist 1994). From a combination of gas accretion and binary black hole coalescence, it is thought that these Pop III-generated seeds may form the SMBHs we observe today (Soltan 1982).

As well-developed as the current effort to understand SMBH growth is, most work has focused on growing the most massive SMBHs. In a Local Group environment, the galaxy morphology, dynamics, and star formation history are all dramatically different than in a higher density cluster. Smaller stellar systems such as disk and dwarf galaxies, have SMBHs with lower masses ($\leq 10^6$ $M_\odot$) or no SMBHs at all for bulgeless galaxies like M33. In cosmological simulations, AGN feedback models create significant uncertainties for black hole growth in these lower mass halos (Booth & Schaye 2009). The morphology of disk galaxies is the result of their poor merger histories. Without major mergers which disrupt disk formation, gas has had enough time to cool and form the disk through secular evolution. Compounding the problem, gravitational wave recoil can plague low mass galaxies preferentially. Recent calculations of binary black hole mergers indicate that gravitational wave recoil can kick a newly merged black hole with a speed as large as $\sim$4000 km s^{-1} (Campanelli et al. 2007). Even moderate kicks can eject a growing SMBH from dwarf or high redshift galaxies (Micic et al. 2006, Volonteri 2007). Given the greater vulnerability to recoil, the questionable importance of AGN feedback, and lack of SMBH in some galaxies, one can argue that SMBH growth may be substantially different for these lightest SMBHs in Local Group type of environments.

In this paper we use Via Lactea 2 (VL-2) evolutionary tracks to begin with an N-body merger tree that mimics the assembly of the Milky Way halo (Diemand et al. 2007,2008). Upon this numerical merger tree we paint semi-analytic recipes for the galaxy and black hole growth. We introduce a model for **prolonged** black hole gas accretion. In addition to gas accretion, black holes grow through mergers with other black holes too. We model SMBH growth from direct mergers including gravitational recoil. Since the recoil velocity is highly dependent on BH spin and orientation, we create $\sim$ 4,000 merger trees to examine the combination of BH spin parameters that favors the $M - \sigma$ relation at redshift zero. We use AGN feedback to suppresses the efficiency of gas accretion, while calibration parameters come from detailed small scale simulations of galaxy merger remnants.

2. METHOD

2. 1. VL-2 DARK MATTER HALO MERGER TREE

VL-2 is the highest resolution cosmological N-body simulation of Milky Way formation and evolution, and evolves a ΛCDM universe with WMAP3 parameters (Ω_M=0.238, Ω_Λ=0.762, σ_8=0.74 and h=0.7). The high resolution region of VL-2 is embedded within a periodic box with a comoving length of 40 Mpc. We combine dark matter halo merger trees obtained from VL-2 evolutionary tracks with an analytical treatment of the physical processes that arise in the dynamics of galaxy and black hole mergers. Our N-body approach stops with the creation of the halo merger tree. We seed dark matter halos with Population III black holes until z=5, following the work of Trenti &

Stiavelli 2009, and follow their merger history from redshift 27.54 to 0 by constructing numerical merger trees interpolating between the snapshots at z$\leq$ 15. To define the structure of each dark matter halo within the N-body generated merger tree, we assume a Navarro, Frenk, & White (hereafter, NFW) density profile (Navarro, Frenk & White 1995). We set the parameters of a given NFW halo using the approach presented in Bullock et al. 2001.

2. 2. SMBH GROWTH PRESCRIPTIONS

In PA, we bundle star formation and AGN feedback, as well as accretion disk microphysics together into gas accretion efficiency parameter; the mass is not restricted to lie on the black hole fundamental plane. Our only guideline is the mass of Sgr A* observed today. We test various BHMFs and various values for the minimum and maximum black hole seed mass. A second effect that is present is gravitational wave recoil (see Section 2.4). In the PA model, the third parameter is the gas accretion efficiency. In our implementation this parameter contains information on how the microphysics acts to suppress accretion onto the black hole, such as SNe feedback, accretion disk physics, etc. We treat all of these processes as free parameters to study the observable consequences at z=0.

Since the black hole growth is so strongly dependent on what fuel is driven to the center during galaxy mergers, it is important to characterize this merger-driven mass growth, including the critical gas physics that may inhibit or strengthen this nuclear supply. We are motivated by numerical simulations that include radiative gas cooling, star formation, and stellar feedback to study the starburst efficiency for unequal mass ratio galaxy mergers (Cox et al. 2008), which finds that the gas inflow depends strongly on the mass ratio of the galaxy. This study parametrizes the efficiency of nuclear star formation (i.e. gas supply and inflow), α, as a function of galaxy mass ratio. In a broader sense, this study shows how much gas is available for either star formation or gas accretion onto the central black hole. These two processes compete for the same gas and the outcome (nuclear cluster versus SMBH) depends on the mass of the host spheroid. The efficiency of gas inflow is described by:

$$\alpha = \alpha_{\mathrm{slope}} \left(\frac{M_{\mathrm{s}}}{M_{\mathrm{p}}} - \alpha_0 \right)^{0.5}, \tag{1}$$

where α_0 defines the mass ratio below which there is no enhancement of nuclear star formation (i.e. gas inflow), and α_{slope} is the fitted slope of the solid line in Cox et al. (2008), Fig 15. Putting these pieces together, the mass accreted by a black hole during $t_{\mathrm{acc}}(r{=}r_{\mathrm{vir}})$ is:

$$M_{\mathrm{acc}} = M_{\mathrm{BH,0}}(e^{\frac{\alpha t_{\mathrm{acc}}}{t_{\mathrm{sal}}}} - 1), \tag{2}$$

where $M_{\mathrm{BH,0}}$ is the initial black hole mass, α is the starburst efficiency (Cox et al. 2008), and t_{sal} is defined above. After t_{df}, the incoming black hole merges with the SMBH at the center and a new SMBH is formed after having accreted gas for t_{acc}. The accretion time and efficiency both implicitly encode the large-scale dynamics of the merger and the bulk gas accretion into the nuclear region, while t_{sal} describes the accretion disk physics.

2. 3. DYNAMICAL FRICTION

Dynamical friction allows massive black hole binaries to form at the center of a galaxy in two ways. First, dynamical friction expedites the merger of two dark matter halos and later the merger of the galaxies they host. Second, dynamical friction from the gas in the disk carries black holes deeper toward the galactic center, where they form binary and eventually merge (Escala et al. 2005). In an effort to better parametrize dynamical friction, Boylan-Kolchin et al. 2008 used N-body simulations to study dark matter halo merging timescales, and confirmed that the Chandrasekhar formalism does underestimate the merger time, by a factor of ≈ 1.7 for $\mathrm{M_p/M_s} \approx 10$ and a factor of ~ 3.3 for $\mathrm{M_p/M_s} \approx 100$. In our initial work (Micic et al. 2007), mergers of dark matter halos trigger the immediate merger of the black holes they are hosting. In this paper, subsequent mergers of the central black holes are delayed to account for dynamical friction of the halos and the black holes within the galaxy. Black holes will not merge if their merger time is larger than a Hubble time, and in that case, we advance the black hole position within the primary halo at each timestep. For the final kpc, we assume that ambient gas and/or non-sphericity will cause two black holes to coalesce within 10 Myrs.

2. 4. GRAVITATIONAL RECOIL

Recent results indicate the recoil can drive a gravitational wave kick velocity as fast as $\sim$4000 $\mathrm{km\,s^{-1}}$ (Campanelli et al. 2007). In reality, much smaller values than this maximum may be expected in gas-rich galaxies due to the alignment of the orbital angular momentum and the spins of both black holes (Bogdanovic et al. 2007). We assume that the orbit is circular, and we take the mass ratio of merging black holes directly from our merger tree. We have the following free parameters: the spin amplitude and orientation of each black hole, and the orientation of the merger. We explore two spin distributions. The K1 model chooses the spin parameters from a uniform distribution, while the K2 model assumes the black hole spins are aligned with the orbital angular momentum (Bogdanovic et al. 2007).

3. RESULTS

Figure 1 which shows the central SMBH mass of the Milky Way analogue as a function of redshift. Black solid line shows mass of Sgr A* when kicks are excluded. The red solid and dashed lines show the K1 and K2 realizations favoring the largest black holes. The blue solid and dashed lines show the K1 and K2 realizations favoring the smallest black holes. Although the final black hole mass lies in a much wider range of masses, these outliers in mass are rare. Figure 2 shows the black hole mass with the largest probability at redshifts z=3.0 (blue); 1.5(red); and 0.0(black). The black line shows that for the K2 case at z=0, the typical black hole mass is in the Sgr A* range 90% of the time. Note that since it is well-accepted that the black hole spin vectors may align with one another before coalescence (Bogdanovic et al. 2007), we consider this our best and most realistic model. However, this does imply a scatter in the M $-\sigma$ relation at the low mass end.

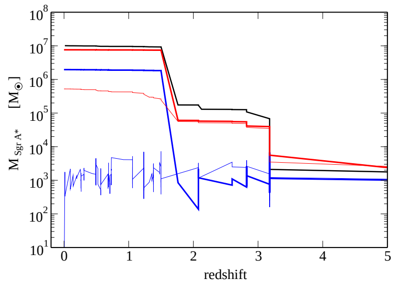

Figure 1: Sgr A* evolution in the PA model for 1000 K1 kick realizations. Black solid line: Sgr A* when kicks are excluded. The red solid and dashed lines show the K1 and K2 realizations favoring the largest black holes. The blue solid and dashed lines show the K1 and K2 realizations favoring the smallest black holes.

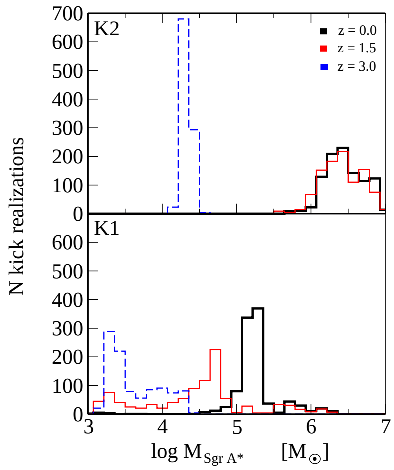

Figure 2: Upper panel: Number of K2 realizations in which Sgr A* reaches a certain mass at a certain redshift, for the PA model. Bottom panel: Number of K1 realizations in which Sgr A* reaches a certain mass at a certain redshift, for the PA model. Histograms are at z=3.0 (blue dashed); z=1.5 (red thin); and z=0 (thick black). In the K2 case, Sgr A* reaches the observed value at z=0 in more than 90% of kick realizations.

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