THE MERGING HISTORY OF MASSIVE BLACK HOLES

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Abstract We investigate a hierarchical structure formation scenario describing the evolution of a Super Massive Black Holes (SMBHs) population. The seeds of the local SMBHs are assumed to be ‘pregalactic’ black holes, remnants of the first POPIII stars. As these pregalactic holes become incorporated through a series of mergers into larger and larger halos, they sink to the center owing to dynamical friction, accrete a fraction of the gas in the merger remnant to become supermassive, form a binary system, and eventually coalesce. A simple model in which the damage done to a stellar cusps by decaying BH pairs is cumulative is able to reproduce the observed scaling relation between galaxy luminosity and core size. An accretion model connecting quasar activity with major mergers and the observed BH mass-velocity dispersion correlation reproduces remarkably well the observed luminosity function of optically-selected quasars in the redshift range 1<z<5. We finally assess the potential observability of the gravitational wave background generated by the cosmic evolution of SMBH binaries by the planned space-born interferometer LISA.

Keywords: cosmology: theory – black holes – galaxies: evolution – quasars: general

1. Introduction

In Volonteri et al. 2003 (Paper I) we have assessed a model for the assembly of SMBHS at the center of galaxies that trace their hierarchical build-up far up in the dark halo ‘merger tree’. We have assumed that the first ‘seed’ black holes (BHs) had intermediate masses, $m_{\text{seed}} \approx 150 m_\odot$, and formed in (mini)halos collapsing at $z \sim 20$ from high-$\sigma$ density fluctuations (cfr. Madau and Rees 2001). These pregalactic holes evolve in a hierarchical fashion, following the merger history of their host halos. During a merger event BHs approach each other owing to dynamical friction, and form a binary system. Stellar dynamical processes drive the binary to harden and eventually coalesce.

The merger history of dark matter halos and associated black holes is followed through Monte Carlo realizations of the merger hierarchy (merger trees)
which allow to track the evolution of SMBH binaries along cosmic time, and analyze how their fate is influenced by the environment (e.g. stellar density cusps).

2. Accretion history

The first stars must have formed out of metal-free gas, with the lack of an efficient cooling mechanism possibly leading to a very top-heavy initial stellar mass function. If stars form above \(260 \, m_\odot\), after 2 Myr they would collapse to massive BHs containing at least half of the initial stellar mass. The mass density parameter of our ‘3.5-σ’ pregalactic holes is \(\Omega_{\text{seed}} \geq 2 \times 10^{-9} \, h\). This is much smaller than the density parameter of the supermassive variety found in the nuclei of most nearby galaxies, \(\Omega_{\text{SMBH}} \approx 2 \times 10^{-6}\). Clearly, if SMBHs form out of very rare Pop III BHs, the present-day mass density of SMBHs must have been accumulated during cosmic history via gas accretion, with BH-BH mergers playing a secondary role. This is increasingly less true, of course, if the seed holes are more numerous and populate the 2- or 3-σ peaks instead, or halos with smaller masses at \(z > 20\) (Madau and Rees 2001).

To avoid introducing additional parameters to our model, as well as uncertainties linked to gas cooling, star formation, and supernova feedback, we adopt a simple prescription for the mass accreted by a SMBH during each major merger assuming that in every accretion episode the BH accretes a mass proportional to the observed correlation between stellar velocity dispersion and SMBH mass. The normalization factor is of order unity and is fixed in order to reproduce both the stellar velocity dispersion and SMBH mass relation observed locally and the optical LF of quasars in the redshift range \(1 < z < 5\).

3. Dynamical evolution of BH binaries

During the merger of two halo+BH systems of comparable masses, dynamical friction drags in the satellite hole toward the center of the newly merged system, leading to the formation of a bound BH binary in the violently relaxed stellar core (Begelman et al. 1980). The subsequent evolution of the binary is determined by the initial central stellar distribution. As the binary separation decays, the effectiveness of dynamical friction slowly declines and the BH pair then hardens via three-body interactions, i.e., by capturing and ejecting at much higher velocities the stars passing close to the binary (Quinlan1996). The hardening of the binary modifies the stellar density profile, removing mass interior to the binary orbit, depleting the galaxy core of stars, and slowing down further hardening. If the hardening continues sufficiently far, gravitational radiation losses finally take over, and the two BHs coalesce in less than a Hubble time. The merger timescale is computed adopting a simple semi-analytical scheme that qualitatively reproduces the evolution observed in N-body simulations.
If was first proposed by Ebisuzaki et al. (1991) that the heating of the surrounding stars by a decaying SMBH pair would create a low-density core out of a preexisting cuspy stellar profile. The ability of SMBH binaries in shaping the central structure of galaxies depends also on how galaxy mergers affect the inner stellar density profiles, i.e. on whether cores are preserved or steep cusps are regenerated during major mergers. To bracket the uncertainties and explore different scenarios we run two different sets of Monte Carlo realizations (Volonteri et al. 2003, Paper II). In the first (‘cusp regeneration’) we assume, that the stellar cusp $\propto r^{-2}$ is promptly regenerated after every major merger event. In the second (‘core preservation’) the effect of the hierarchy of SMBH binary interactions is instead cumulative. The simple models for core creation described above yields core radii that scale almost linearly with galaxy mass, $r_c \propto M_0^{0.8-0.9}$ in the range $10^{12} < M_0 < 4 \times 10^{13} m_\odot$. A similarly scaling relation was observed by Faber et al. (1997) in a sample of local galaxies. A better test of our model predictions against galaxy data is provided by the ‘mass deficit’, i.e. the mass in stars that must be added to the observed cores to produce a stellar $r^{-2}$ cusp (see fig. 1). The cusp regeneration model clearly underestimates the mass deficit observed in massive ‘core’ galaxies, while the core preservation one produces a correlation between ‘mass deficit’ and the mass of nuclear SMBHs with a normalization and slope that are comparable to the observed relation.
4. Gravitational waves from SMBH binaries

We have computed the gravitational wave (GW) background (in terms of the characteristic strain spectrum) due to the cosmic population of SMBHs evolving along the lines discussed in the previous sections. Details and a complete discussion can be found in Sesana et al. 2003.

Using a linearized GR theory of GW emission and propagation, framed in a cosmological context, we find that the broad band GW spectrum can be divided into three main different regimes (fig. 2): for frequencies \( \lesssim 10^{-9} \) Hz, the background is shaped by SMBH binaries in the three-body interactions regime (orbital decay driven by stellar scattering); in the intermediate band, \( 10^{-9} \lesssim f \lesssim 10^{-6} \) Hz, GW emission itself accounts for most of the potential energy losses, and the strain has the "standard" \( f^{-2/3} \) behaviour; finally, for \( f \gtrsim 10^{-6} \), the GW spectrum is formed by the convolution of the emission at the last stable orbit from individual binaries. In the first two regimes, the strain is dominated by rare low redshift events (\( z \lesssim 2 \)) involving BHs genuinely supermassive. At larger frequencies the contribute from smaller and smaller masses starts dominating.

We have considered the possible future observability of the GW background by the planned LISA interferometer, showing that one year observation would suffice to detect the GW background due to SMBH binaries. Such background should overcome that due to extragalactic WD-WD binaries. In the LISA window \( 10^{-4} \lesssim f \lesssim 0.1 \) Hz, the main GW sources are BH binaries in the mass range \( 10^3 \lesssim M \lesssim 10^7 \, M_\odot \), with a relevant contribution from \( 3 \lesssim z \lesssim 20 \). In the nHz regime, probed by pulsar timing experiments, the amplitude of the characteristic strain from coalescing SMBH binaries is close to current experimental limits (Lommen 2002, see also Wyithe and Loeb 2003).

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