RevMexAA (Serie de Conferencias), **17**, 333–334 (2003)

THE MERGING HISTORY OF BINARY SUPERMASSIVE BLACK HOLES

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RESUMEN

Presentamos un modelo de ensamblaje de Agujeros Negros Supermasivos (ANSMs) en el centro de galaxias siguiendo su formación jerárquica desde épocas tempranas y trazando sus historias de acreción y fusión. Supusimos que las semillas de los ANSMs locales son ANs de masa intermedia, $m_{seed} \approx 150 m_\odot$, producto de primeras estrellas en (mini)halos que colapsan a $z \sim 20$. A medida que estos hoyos pregalácticos se incorporan a través de una serie de fusiones en halos mayores y mayores, ellos por fricción dinámica se asientan en el centro, acretan gas del remanente de la fusión para convertirse en supermasivos, forman un sistema binario y eventualmente coaliscionan.

ABSTRACT

We present a model for the assembly of Supermassive Black Holes (SMBHs) at the center of galaxies following their hierarchical build-up, from early times, tracking their merging and accretion histories. We assumed that the seeds of the local SMBHs are intermediate mass BHs, $m_{seed} \approx 150 m_\odot$, endproduct of the first stars in (mini)halos collapsing at $z \sim 20$ from high-σ density fluctuations. 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.

Key Words: **COSMOLOGY: THEORY — BLACK HOLES — GALAXIES: EVOLUTION — QUASARS: GENERAL**

Galaxy Evolution: Theory and Observations (Cozumel, Quintana Roo, México, 8-12 April 2002)
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1. FROM PRIMORDIAL SEEDS TO SUPERMASSIVE BLACK HOLES

We address the problem of following the evolution of BHs with redshift within dark matter (DM) halos. We perform Montecarlo realizations of halo merging histories (merger trees) using simple semi-analytical recipes describing gas accretion and the evolutionary timescale of binary SMBHs systems. We developed a Montecarlo algorithm to generate binary merger trees based on the Extended Press & Schechter formalism (EPS, Bower, 1991, Lacey & Cole 1993). Using this algorithm, we generated a set of merging histories of dark matter halos, starting from $z = 20$ in a ΛCDM cosmology ($\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h_0 = 0.7$, $\Omega_b = 0.04$, $n = 1$, $\sigma_8 = 0.93$).

We assume that one seed BH of mass $\approx 150 m_\odot$ forms in halos collapsing at $z \sim 20$ from the high-σ peaks (3.5-σ) of the primordial density field as end-product of the first stars. These tiny seeds must grow in mass of several orders of magnitude to become supermassive: they merge and accrete gas. Hydrodynamic simulations of major mergers have shown that a significant fraction of the gas in interacting galaxies falls to the center of the merged system (Mihos & Hernquist 1994, 1996): the cold gas may be eventually driven into the very inner regions, fueling an accretion episode and the growth of the nuclear BH. We therefore assumed that BHs accrete gas only after a major merger, and the accreted mass is added to the BH in the more massive progenitor halo. In local galaxies SMBH masses, $M_{\rm BH}$, are strongly connected with the stellar velocity dispersion (Merritt & Ferrarese 2001, Gebhardt et al. 2000) of their host galaxies, σ_c. To avoid introducing additional parameters to our model, as well as uncertainties linked to gas cooling, star formation, and supernova feedback, we simply rescale the accreted mass, $m_{\rm acc}$, with the observed $M_{\rm BH} - \sigma_c$:

$$\Delta m_{\rm acc} = 1.7 \times 10^8 \, m_\odot \mathcal{K} \, \sigma_{c,200}^{4.6}, \qquad (1)$$

the normalization, $\mathcal{K}$, of order unity, is set requiring to reproduce both the $M_{\rm BH} - \sigma_c$, relation at $z = 0$ and the luminosity function (LF) at various redshifts. Our simple model reproduces reasonably well the faint end of the observed LF of optically-selected quasars in the redshift range $1 < z < 4$. The slope at low luminosities matches the one inferred by Boyle et al., and is considerably flatter than the extrapolation of the SDSS power-law. Modeling gas accretion onto BHs with the recipes just described we find that, along cosmic history, most of the final mass of SMBHs come from gas accretion, rather than from BH merging.

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2. INTERACTIONS AMONG BHS

When two galaxies with a central BH merge, we follow the dynamical evolution of the system, from early stages to final coalescence. *First*, dynamical friction, starting with the merging of the DM halos and ending with the neighboring of the stellar bulges, leads to the formation of the SMBH binary. Dynamical friction against the BHs is indeed efficient only during major mergers. In fact, during minor mergers mass stripping is likely to leave the satellite SMBH naked from its stellar envelope, too far apart from the primary SMBH to form a binary system. Within our scheme these BHs remain wandering in galaxy halos through successive mergers. *Second*, at parsec-scale, the binary system starts to shrink through three-body interactions with the surrounding stars, mainly via close encounters (hardening of the binary); the energy transfer from the SMBHs to the stars causes the ejection of the latter, slowing the coalescence and creating a density core (Quinlan 1996; Merritt 2000; Milosavljevic & Merritt 2001). *Third*, at sub-parsec scales, when the binary has shrunken down to a point where the emission of gravitational radiation becomes efficient, the two BHs can coalesce. Total coalescence timescale can be as short as 6×10^7 years up to several Gyrs, the mean value being 0.3 ± 0.1 Gyrs.

The hardening phase can be longer than the time before another merger drives an intruder BH within the radius of gravitational influence of the shrinking binary, so triple interactions happen. After such an encounter the binding energy of the binary increases $\propto m_{\rm int}/m_{\rm bin}$, where $m_{\rm int}$ is the mass of the intruder and $m_{\rm bin}$ is the mass of the binary. Conservation of energy and momentum in the interaction allows to estimate the recoil velocity of the binary and intruder. If the kick velocity of the binary and/or single BH exceeds the escape speed from the halo, $v_{\rm esc}$, the hole(s) will leave the galaxy altogether, creating an "intergalactic black hole" population. The recoil velocity of the single hole results larger than $v_{\rm esc}$ in 99% of encounters. The binary is ejected instead in only 12% of the encounters and typically at very high redshifts. Our scheme, therefore, predicts, along nuclear SMBHs hosted in galaxy bulges, a number of BHs wandering within halos, which, in most of the cases, are the result of minor mergers rather than of scattering and exchanges, and intergalactic BHs as well.

At $z = 0$ wandering BHs and intergalactic contribute respectively with a 3% and with a 8% to the total mass density in BHs, $\simeq 4 \times 10^5 m_\odot/{\rm Mpc}^3$ (h=0.7). The mass density in nuclear BHs is $\simeq 3.5 \times 10^5 m_\odot/{\rm Mpc}^3$, within 30% to the value given by Merritt & Ferrarese (2001).

3. BINARY SMBHS AND BINARY QSOS

On average, along the cosmic history, only a fraction $\lesssim 10\%$ of the BHs hosts a binary system; at late epochs such fraction can be larger, reaching a peak of $\simeq 15\%$ at $z = 0$. A fraction $\approx 60\%$ of the SMBH binaries at $z = 0$ has separation larger than 0.1 kpc and are still in the process of falling to the center due to dynamical friction, while $\approx 10\%$ is in an advanced stage of hardening ($a < 10$ pc). The former class would be recognizable as multiple nuclei.

Binary quasars are a different, intrinsically rare phenomenon, as both SMBHs must be active at the same time. Observationally, 16 pairs are known in a sample of $\sim 10^4$ observed quasars, and among these 16, the confirmed physical associations are less than 10 (Kochanek, Falco & Muñoz 1999).

Given our accretion recipe, we found a fraction of binary quasar with $L > 0.01 L_*$ which is $\simeq 1 - 3 \times 10^{-3}$ at $z < 4$. A similar fraction is found taking a threshold $L > 0.1 L_*$.

Details of the method adopted and relative results are described in Volonteri et al. 2002.

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