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Dynamics and fueling of supermassive black holes in gas-rich galaxy binary mergers

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Abstract. We study the dynamical evolution of supermassive black holes hosted in gas-rich galaxies that undergo a merger. Binary mergers among equal and unequal mass disk galaxies are followed using high-resolution N-Body/SPH simulations inclusive of radiative cooling, star formation, and shock heating. We find that equal-mass mergers lead always to the formation of a *close BH pair* at the center of the remnant with separations limited solely by the adopted force resolution of $\sim$ 100 pc. In unequal-mass mergers instead, the pairing process depends sensitively on how the internal structure of the merging galaxies is altered by the inclusion of a gaseous component. *Gas cooling* facilitates the formation of a *close BH pair* by increasing the resilience of the less massive galaxy to tidal disruption. In the absence of dissipation, the galaxy is instead entirely disrupted before the merger is completed, leaving a BH wandering at a distance from the center comparable to the effective radius of the merger remnant. Large inflows of gas are observed which always end in the formation of a massive rotationally supported circum-nuclear disk that surrounds the supermassive BH(s). The disks have sizes, masses and rotational velocities close to the one observed spectroscopically for a few AGNs and ULRIGs. The simulations of dissipative unequal-mass mergers show that a central inflow of gas can initiate its course toward the central BH of the less massive tidally perturbed galaxy before the merger goes to completion. This suggests that in unequal-mass galaxy binary mergers *nuclear activity is more likely associated to the less massive component of the interacting binary and that a single QSO is active in a merger* .

Key words. Black hole physics and dynamics– Interacting galaxies – AGN activity – Cosmology

1. Black Holes in a Cosmological Context

Since the pioneering work of Toomre, binary mergers among gas-rich disk galaxies are considered to be the principal process for the formation of bright elliptical galaxies. Mergers destroy rotational equilibria, transform stellar disks into more spheroidal configurations supported by dispersion velocities, and drive large-scale gas inabilities that may end in massive starbursts. In case a nuclear supermassive black hole (BH) is present in an interacting galaxy, inflows of gas toward the central BH can also drive large accretion powered energy outflows. Thus nuclear activity and starbursts appear to be phenomena that co-exist, when driven by violent dynamical events such mergers, leaving fingerprints in the underlying dynamical structure.

HST spectroscopic observations have unambiguously indicated that in our local Universe, bright elliptical galaxies and spirals with prominent bulges host in their cores supermassive BHs, fossil records of an earlier quasar phase. Their mass $M_{\rm BH}$ seem to correlate tightly with the mass of the stellar spheroid, or, alternatively, with the depth of the potential well measured by the line-of-sight stellar dispersion velocity σ, demonstrating the joint link between galaxy and BH formation and evolution (Ferrarese & Merritt 2000; Gebhardt et al. 2000). Feedback from the AGN output can sterilize star formation when sufficient energy or momentum is injected into the gas on the dynamical time scale shaping properties of the bulge further away from the BH gravitational sphere of influence $r_{\rm BH} \sim GM_{\rm BH}/\sigma^2$ (Silk & Rees 1998; Burkert & Silk 2001). Even on much larger scales AGN energy outflows can deposit entropy in the hot intracluster medium (Begelman 2003). This phenomenon has thus important implications for cosmology whose main goal is to trace the history of cosmic structures (for a physical model of the coevolution of QSOs and their spheroidal hosts see Granato et al. 2004).

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According to the standard paradigm, structures in the Universe are the end result of a complex hierarchy of mergers and accretion of gas-rich dark-matter dominated pre-galactic halos. If mergers are the ruling events that occur in (pre-)galactic structures hosting seed BHs, BH evolution necessarily accompanies that of galaxies along cosmic history. Thus, a natural prediction of any hierarchical clustering cosmology is the existence of *pairs of active nuclei*, and *binary black holes* that would testify the mode in which galactic structures assemble. AGN pairs can be viewed as double nuclear cores powered by accretion onto their respective BHs active when the two galaxies, a few kiloparsecs apart, have not completed their merger yet. Binary BHs are instead double BHs that are physically bound and form a Keplerian system deeply embedded in a stellar or gaseous medium.

Observationally a number of phenomena has been attributed to the presence of binary BHs, including helical radio-jets, periodicities in blazar lightcurves (Komossa et al. 2003), but none compelling. The interesting case is NGC 6240, the nearest member of the class of ULRIGs, showing two nuclear hard X-ray active regions, possibly two active BH in a pair at relative separation of a few kpc. This is the most extraordinary example where a starburst in a merger (identified with the presence of tails) coexist with a two AGNs.

The formation and growth of BHs has been recently studied in a cosmological context at statistical level (e.g., Volonteri et al. 2003; Menci et al. 2004). These models trace back the evolution of BHs nested inside the cores of dark matter halos. Simple physical recipes are added in a merger tree diagram to describe the history of the baryonic component and the evolution of accreting BHs in galactic subunits. The AGN luminosity function at different cosmic times,the $M_{\rm BH}$ versus σ relation, and the QSO luminosity and local BH mass density are explained in this context, imposing that the BH mass derives mainly from accretion of gas funneled into the core at a rate close to the Eddington limit. Volonteri et al. (2003) were the first to follow the assembly of seed BHs born in population III objects, tracing their dynamics in detail, i.e., including time scales for the sinking of the BHs by dynamical friction, keeping non obvious dependences such as eccentricity corrections and mass loss by underlying tidal fields (Colpi et al. 1999). They included the possibility that tidal stripping of mass around the nuclear BHs may give origin to "wandering" BHs, i.e., BHs that have failed to merge with the galaxies, as it was first suggested by Governato et al. (1994). The formation of BH binaries in a cosmological context is becoming an important issue: Coalescing binary BHs with masses between 10^5-10^7 $M_\odot$ are expected to generate the clearest gravitational wave signals that will become detectable with the space-based interferometer LISA. LISA can potentially bring information of the entire process of clustering of structures up to redshift $z \sim 20$ probing the Universe in its cosmic dawn (Sesana et al. 2004). It is our aim to explore in detail the hydrodynamical processes that accompany a merger between galaxies with BHs, to study the effect of a gaseous dissipation in the orbital evolution and fueling of the BHs. This is complementary to the semianalytical approach.

The formation and subsequent dynamical evolution of BH pairs depend on how efficiently the galactic cores hosting the holes lose angular momentum on account of dynamical friction during the merging process. Four main stages has been highlighted by Begelman et al. (1980): (1) BH drag toward the center of the common mass distribution by dynamical friction acting on both interacting systems; (2) formation of a BH pair as the BHs loose angular momentum due to the interaction with the background; (3) slow hardening of the binary BH by three-body scattering with the surrounding stars plunging along low angular momentum orbits; (4) further shrinking of the binary BH orbit due to emission of gravitational waves and eventual coalesce.

The early phases (1) and (2) have been investigated numerically in the past by a number of authors (e.g., Governato et al. 1994; Milosavljević & Merritt 2003,including phase (3)). However, the galaxy models in these studies were idealized, spherical stellar systems with no link to current models of structure formation. These models could at most faithfully represent real galaxies and hence the depiction of the first two phases was incomplete. Hence, both the larger scale dynamical evolution of the merging systems and the cosmological framework were missing. Moreover, these studies included no dissipative components, and thus did not explore the role of gas in the formation and evolution of a supermassive BH pair. Notable exceptions are the studies by Escala et al. (2004), who showed that the presence of gas in phase (3) causes continuing loss of orbital angular momentum rapidly reducing the BH relative separation to distances where gravitational radiation and coalescence is efficient. However, if and how their initial conditions are related to the larger scale dynamics involved in galaxy merging is still unclear.

In this proceeding we report on the effects of gaseous dissipation on the fate of supermassive BHs during equal- and unequal-mass binary galaxy mergers, using for the description of the interacting galaxies numerical simulations with unprecedented resolution and initial conditions consistent with the LCDM paradigm.

2. Numerical Simulations

We performed a number of high-resolution binary merger simulations of disk galaxies with mass ratios of 1:1 and 4:1. We simulate mergers in which gas behaves adiabatically, and mergers in which we include radiative cooling and star formation. For details we refer to Kazantzidis et al. (2004). The simulations were performed with GASOLINE, a multi-stepping, parallel TreeSPH N-body code (Wadsley et al. 2004). Each galaxy consists of a spherical and isotropic Navarro et al. (1996) dark matter (DM) halo, an exponential disk (with gas fraction when present of 10% of the total disk mass), and a spherical, Hernquist (1990) non-rotating bulge. For the basic galaxy model we adopted parameters from Milky Way model A1 of Klypin et al. (2002). Specifically, the DM halo had a virial mass of $M_{\rm vir} = 7 \times 10^{11}\, h^{-1} M_\odot$, a concentration $c = 12$, and a dimensionless spin parameter of $\lambda = 0.031$. The mass, thickness and scale length of the disk were $M_{\rm d} = 0.04 M_{\rm vir}$, $z_0 = 0.1 R_{\rm d}$, and $R_{\rm d} = 2.45 h^{-1}$ kpc, respectively. The bulge mass and scale radius were $M_{\rm b} = 0.008 M_{\rm vir}$ and $a = 0.2 R_{\rm b}$, respectively. The companion galaxy is either a replica of the same model (in equal-mass mergers) or a system containing one-fourth of the mass. To each of the galaxy models was added a particle at the center of the bulge component that represents a central supermassive BH. For the largest galaxy model we used a mass equal to $M_{\rm BH} = 3 \times 10^6 M_\odot$.

3. The dynamics of BH pairing

We find that the galaxies merge in three to five orbits (between 5.5 to 7 Gyr). In equal-mass mergers, the cuspy potentials of both galaxies are deep enough to allow the survival of their inner regions until orbital decay by dynamical friction is complete. This result holds for both adiabatic and dissipational mergers. In gasdynamical runs large gas inflows are observed. During the first two orbits a strong spiral pattern appears in both the stellar and the gaseous component and mild non-axisymmetric torques redistribute mass and angular momentum, driving approximately 20% of the gas towards the center. The central bulges stabilize the galaxies against bar formation. Shortly before the galaxies merge, a second much stronger inflow occurs caused by strong tidal torquing. This inflow results in a significant central concentration of cold gas. In this case, more than 80% of the gas that was originally in the disks is collected within the central 500 pc. In runs with star formation these large inflows are associated with a central starburst and more than 90% of the central gas distribution is converted into stars in less than 10^8 yr. The peak star formation rates range from 30 to $> 100 M_\odot {\rm yr}^{-1}$, comparable to those of luminous infrared galaxies. As illustrated in Figure 1, the two BHs end up orbiting at the center of the remnant on eccentric orbits and at a separation comparable to the resolution of our simulations of ~ 100 pc.

In unequal-mass mergers, the outcome depends sensitively on the presence or not of dissipation, as shown in Figure 1. In adiabatic runs, the tidal disruption of the satellite galaxy at about 6 kpc from the center leaves its supermassive BH wandering at a distance that prohibits the formation of a close pair. In dissipational runs, the situation is reversed as the gas inflow becomes particularly strong in the light galaxy. We measured an inflow of about $3 M_\odot$ yr^{-1} within the central kiloparsec compared with $< 0.5 M_\odot {\rm yr}^{-1}$ for the larger galaxy. This striking difference in the gas inflows is attributed to a tidally induced stellar bar observed in the satellite galaxy approximately 1.5 Gyr before the final passage. More than 50% of the gas is funneled into the center owing to gas shocking in the bar potential. At this stage the companion galaxy has about 20% more gas within its central ~ 1 kpc relative to the larger galaxy. *This is strongly suggestive that dynamical destabilization in the lighter galaxy induced by the tidal field of the heavier companion can trigger activity in the less massive galaxy, before the merger is completed.* Dissipation enables the core of the lighter galaxy to survive complete tidal disruption by deepening its potential well and facilitates the formation of a supermassive BH pair separated by ~ 100 pc similarly to the equal-mass mergers.

3.1. Massive Circumnuclear Disks

The large inflows observed in the cooling and star formation runs always produce a rotationally supported nuclear disk with a size in the range $1-2$ kpc, as illustrated in the right panels of Figure 1. They show significant spiral patterns (left panels of Fig. 1) which can promote strong inflows that may start feeding the BHs, setting the conditions used by Escala et al. (2004) for tracing the subsequent evolution. These disks are tilted by several to a few tens of degrees relative to the orbital plane of the galaxies. They have peak rotational velocities and gas masses in the range of $250-300$ km s^{-1} and $\sim 10^8 - 10^9 M_\odot$, respectively, and they are resolved by more than 10^4 particles. Nuclear disks of *molecular* gas of a few hundred parsec to a kiloparsec scale have been identified spectroscopically for few AGNs and ULRIGs. The observed sizes, masses, and rotational veloci-

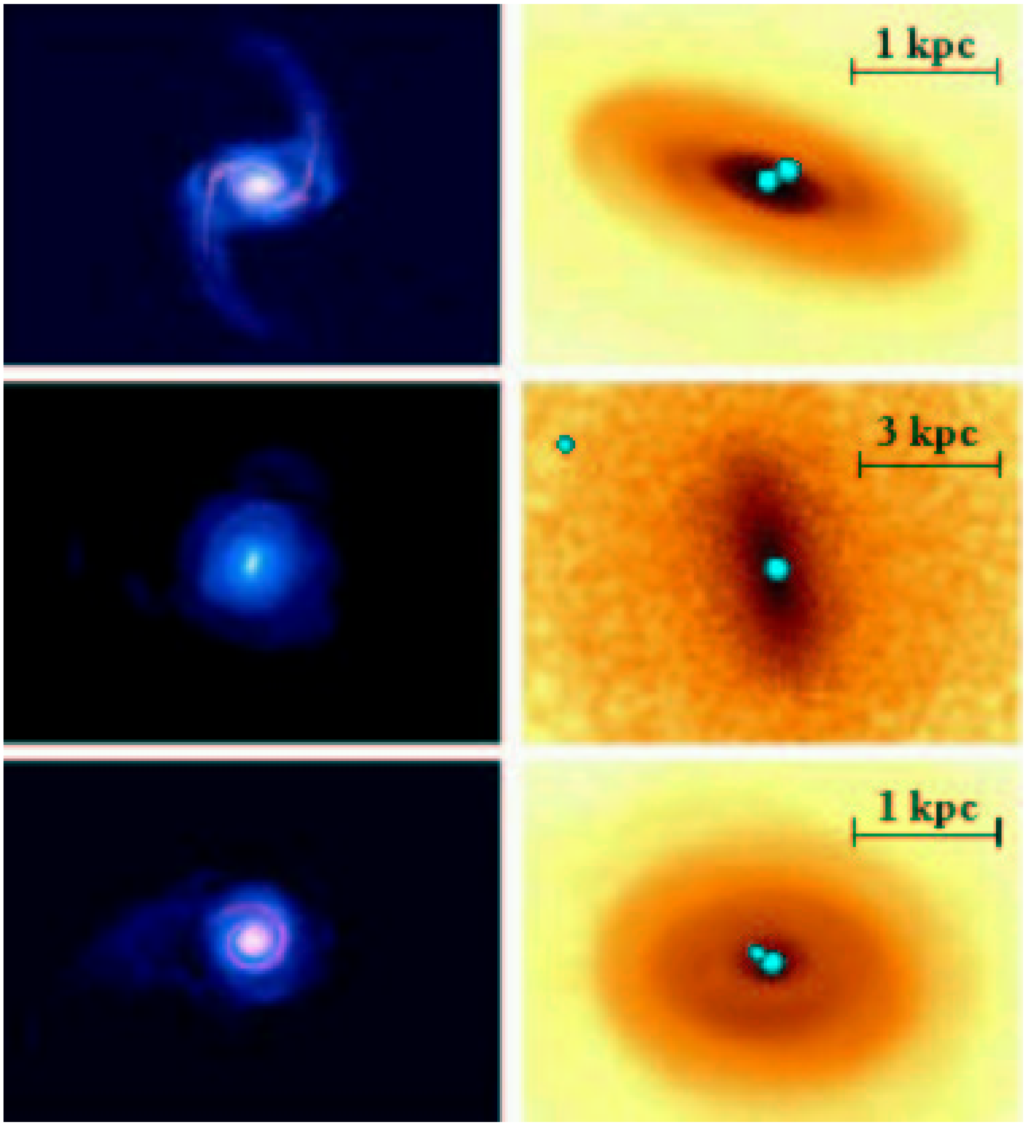

Fig. 1. Final position of supermassive BHs (*filled circles*) in a subset of merger simulations. The large scale (*left*) and small-scale (*right*) structure of the remnants projected onto the orbital plane is also shown. All frames correspond to remnants that were allowed to relax for several dynamical times after the merger was complete. The top and bottom rows of panels present results for the coplanar 1:1 and 4:1 mergers with gas cooling, respectively. The middle rows of panels corresponds to the coplanar adiabatic 4:1 merger. The frames on the left show the logarithmic baryonic surface density maps and are 320×230 kpc. Blue and red maps are used for the stellar and gaseous component, respectively, and adaptive smoothing is used to preserve details in high-density regions. The top and bottom frames on the right are enlarged by a factor of 100 and show the central nuclear gaseous disk. The middle frame on the right shows the stellar distribution of the merger remnant and is enlarged by a factor of 30.

ties are comparable to those measured in our simulations.

4. Conclusions

Gaseous dissipation influences considerably the outcome of binary mergers of galaxies containing supermassive BHs. Most importantly, it controls the BH pairing process in unequal-mass mergers by modifying the central structure of the companion galaxy and enabling it to survive complete tidal disruption. This result suggests that semi-analytic models of hierarchical BH growth that neglect the effect of dissipation likely overestimate the number of wandering SMBHs in MW-sized galaxies (Sesana et al. 2004), since the majority of these result from mergers with mass ratios less than 3:1. Reducing the number of wandering SMBHs in account of our new results will be of great interest for the LISA experiment.

Finally, the simulations of dissipative unequal-mass mergers show that the timing of central inflows in the two galaxies can be different. Indeed, approximately 1 Gyr before the completion of the merger, the core in the less massive galaxy reached a factor of 2 larger mass and experienced a more pronounced starburst compared to that of the largest galaxy. *Nuclear activity in the lighter interacting galaxy can accompany the starburst, before coalescence*. This might explain the existence of galaxies like Markarian 231 that has two nuclei, yet only one of them hosts an AGN and undergoes intense star formation.

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