Co-Evolution of Central Black Holes and Galaxies
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Growing Supermassive Black Holes in Cosmological Simulations of Structure Formation

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Abstract. We discuss a numerical model for black hole (BH) growth and feedback that allows simultaneous tracking of the evolution of galaxies and their central BHs in fully cosmological simulations. After describing the main features of the numerical model adopted, we show how BHs in these simulations affect the properties of their host halos and how this in turn impacts the growth of the BHs themselves. We also present results from a set of simulations specifically designed to address the issue of BH assembly in the early Universe and discuss whether or not different extensions of the model, in particular rapidly spinning BHs and gravitational recoils, can hamper the formation of the first bright quasars.

Keywords. black hole physics, methods: numerical, cosmology: theory

1. Introduction

A large body of observational data (e.g., Kormendy & Richstone 1995; Magorrian *et al.* 1998) collected over the past two decades has established that black holes (BHs) are ubiquitous inhabitants of possibly all galaxies with a central bulge component. Recent observational findings (e.g., Tremaine *et al.* 2002; Häring & Rix 2004) have shown that BHs are tightly linked to the properties of their host galaxies. From a theoretical standpoint it is still unclear why a relationship between BHs and galaxy bulges should exist or how it evolves with redshift. Nonetheless, the very existence of this relationship is telling us that BHs are possibly affecting the properties of their hosts and that in turn BH growth is dependent on the structure and dynamical state of galaxies. This remarkable finding has prompted vigorous theoretical research (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000) aimed at understanding the physical mechanisms responsible for the interdependent evolution of BHs and galaxies. Here we attempt to address these issues by means of fully self-consistent cosmological simulations where a number of the complex and non-linear processes regulating galaxy formation can be treated accurately. Even though numerical limitations impose inevitable approximations encapsulated in the form of sub-resolution grid modelling, cosmological simulations can provide a more complete view on the co-evolution of galaxies and their central BHs.

2. Methodology

For our numerical simulations we use the massively parallel Tree-SPH code GADGET-3 (Springel 2005a). Besides standard physical processes implemented in the code (gravity,

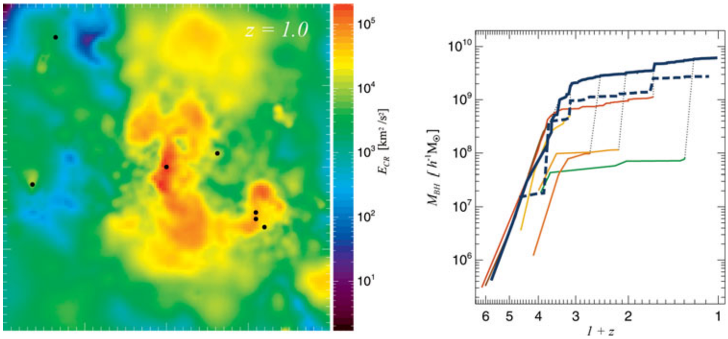

Figure 1. *Left:* Projected mass-weighted cosmic-ray energy per unit mass. The map shows a region centered on the most massive galaxy cluster at $z = 1$, and is $4h^{-1}$Mpc on a side. *Right:* Merger tree of the most massive BH at $z = 0$ in the simulation. The mass growth of the BH's first progenitor is shown by the thick blue line. Thin lines denote the most massive secondary progenitors that merge with the first progenitor, as shown with dotted lines. The thick dashed line is the cumulative mass of all secondary progenitors.

radiative hydrodynamics of optically thin plasma of hydrogen and helium, UV background) we adopt a multiphase model for star formation and supernova feedback (as described by Springel & Hernquist 2003), as well as optional star-burst powered galactic winds with $v_{\rm wind} \sim 480\,{\rm km\,s^{-1}}$. Additionally, we consider a model for BH growth and feedback as implemented by Springel *et al.* (2005b) and Sijacki *et al.* (2007). In §5, we discuss several extentions of the BH model, where we explore the effects of BH spins and of gravitational wave-induced recoils during BH mergers (Sijacki *et al.* 2009).

3. Cosmological Simulations of AGN-Heated Galaxy Clusters

We first discuss how BH growth proceeds in galaxy groups and clusters, and what the resulting signatures of AGN heating are. As an illustrative example, in the left-hand panel of Figure 1, we show a map of a simulated galaxy cluster at $z = 1$, subject to BH feedback (for further details see Sijacki *et al.* 2008). A series of hot, buoyantly rising bubbles inflated by the central BHs can be clearly seen. These bubbles, while moving through the cluster atmosphere, are stirring and heating the surrounding gas. Interestingly, a smaller mass halo visible in the lower right corner of the map is also hosting an active supermassive BH. The close interaction of these two halos, which will eventually merge, is not only influencing the way bubbles propagate through the intracluster medium but also determines the central gas supply available for BH accretion. In the right-hand panel, the mass evolution of the most massive BH of this galaxy cluster is shown (Sijacki *et al.* 2007). The BH grows most rapidly at high redshifts and gains half of its mass before $z \sim 1.5$. A detailed analysis of the BH's merging history reveals that roughly 55% of its final mass is due to gas accretion occurring in situ, while that remaining comes from mergers with other BHs. The results shown in Figure 1 demonstrate that it is possible to simultaneously reproduce realistic AGN-driven bubble morphologies and BH masses in fully cosmological simulations. But in which way do BHs affect the properties of their hosts? BH feedback has some generic features: the central baryon density is reduced (both in gas and stars), and the temperature in the innermost regions is increased. The mass deposition rate towards the central regions is decreased, such that the excessive over-cooling in simulations is prevented. This brings the simulated properties of galaxy clusters in much better agreement with observations.

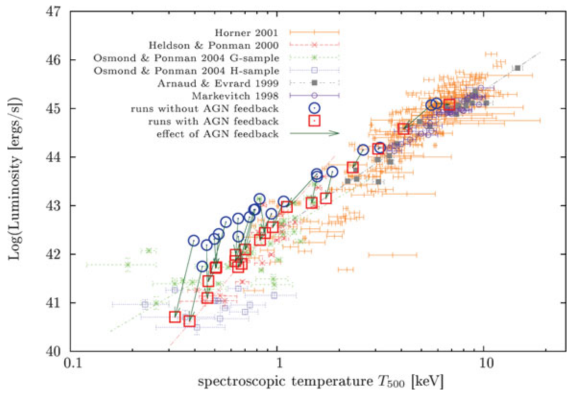

Figure 2. X-ray luminosity–temperature scaling relationship for a sample of simulated galaxy groups and clusters (circles: no AGN; squares: with AGN feedback). A number of observational data points are shown as well, as indicated in the legend.

By performing high-resolution simulations of a large sample of galaxy groups and clusters (see Puchwein *et al.* (2008) for details) we were able to determine the signatures of AGN feedback in a statistical sense. This is illustrated in Figure 2, where we show the scaling relationship between X-ray luminosity and gas temperature. A number of observational data points are shown for comparison. AGN feedback drastically reduces the X-ray luminosity, especially on the scales of groups, while the temperature stays similar or is somewhat reduced. This brings the simulated L_X–T scaling law in a very good agreement with observational findings, which has been a long standing problem in our theoretical understanding of galaxy clusters.

4. Impact of AGN Feedback on Galaxy Formation

We have simulated a set of uniform cosmological boxes at high resolution (Sijacki *et al.* 2007) to study the impact of AGN feedback on a representative sample of galaxies. In the left-hand panel of Figure 3, we show the BH mass density as a function of redshift in one of the simulated boxes, of $25h^{-1}$ Mpc on a side. Different curves, from bottom to top, indicate the BH mass density obtained by increasing the numerical resolution. For $z < 3$, the BH mass densities are very similar, indicating good numerical convergence. At $z = 1$ we find a BH mass density of $\sim 2.5 \times 10^5 M_\odot\,\mathrm{Mpc}^{-3}$, which is consistent with observational findings (e.g., Fabian *et al.* 1999).

Using cosmological simulations where galaxies with stellar masses from $\sim 10^8\,M_\odot$ to $\sim 10^{11}\,M_\odot$ have been resolved, we have measured the BH mass–stellar mass relationship, which is shown for $z = 1$ in the right-hand panel of Figure 3. The dashed line denotes the observational estimate by Häring & Rix (2004) for a local sample of galaxies. For BH masses above $\sim 5 \times 10^6\,M_\odot$, the simulated and observed relations agree very well, indicating that possibly not too much evolution is expected in this relation from $z = 1$ to $z = 0$. Instead, for lower BH masses there is a clear discrepancy that is, however, mitigated if galactic winds are included in the simulation. The reason for this is that such low-mass BHs cannot substantially modify the stellar masses of their hosts, which come out too large in the model, while the kinetic energy of star-burst powered winds is sufficient in placing these galaxies on the observed relationship. This is a very interesting point, suggesting that: (i) BHs in these small mass galaxies should be bigger (or have larger feedback effects) than in the simulation, or (ii) galactic winds are more important for the properties of small mass galaxies than the feedback effects from their central

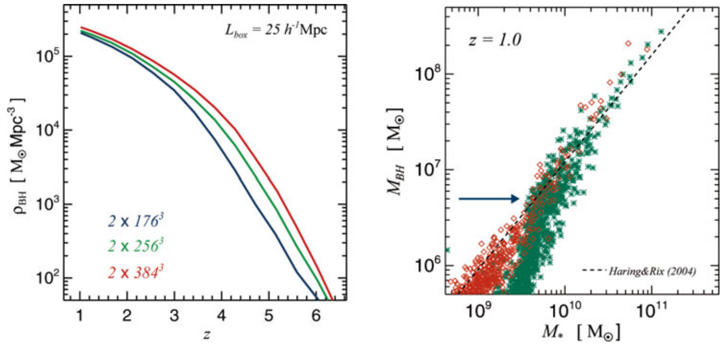

Figure 3. *Left:* Comoving BH mass density evolution with redshift in a simulated box of $25h^{-1}$ Mpc on a side. Different curves indicate the same simulation performed at three different resolutions. *Right:* BH mass–stellar mass relationship at $z = 1$. Star symbols are for simulations without galactic winds, while diamond symbols are for the run where galactic winds have been included.

BHs, or (iii) the observed relationship actually evolves at the low mass end for $z > 0$. While neither of the three scenarios can be excluded at the moment, the second one appears most likely. Future observations of high-redshift galaxies with systematic biases under control (see, e.g., Merloni *et al.* 2009) could help discriminate among these three possibilities.

5. Growing the First Bright Quasars in Cosmological Simulations

In §3 and §4, we have highlighted some of the basic properties and predictions of our cosmological BH model, from the scales of galaxies to the scales of galaxy clusters, over a range of redshifts. Here, we want to discuss a very important benchmark for this model — the existence of quasars at $z = 6$. Given that luminous quasars at $z = 6$ are very rare, we have resimulated the most massive halo from a very large cosmological box (the "Millennium simulation," Springel *et al.* 2005c) at $z \sim 6$ (for details see Sijacki *et al.* 2009). The density map of this halo is illustrated in Figure 4, where we compare the original resolution (left-hand panel) with the case where we have increased the mass resolution by a factor of 10^3 (right-hand panel). To reliably track the growth of supermassive BHs at these very high redshifts, it was mandatory to reach a very high numerical resolution, so as to achieve numerical convergence in the BH accretion rate (as we have explicitly checked).

In the left-hand panel of Figure 5, we show how the mass of the most massive BH in the simulated volume evolves with redshift, at three different resolutions. In the right-hand panel, instead, we plot the bolometric luminosity of this BH and compare it with recent observational estimates. The results shown in Figure 5 are very encouraging: the same model which produces a realistic BH mass density at low redshifts and which prevents over-cooling in galaxies and galaxy clusters can also account for the existence of bright quasars at $z = 6$, which have masses, luminosities, and a space density in very good agreement with observations.

In the last couple of years, general relativistic simulations of merging BH binaries have provided accurate estimates of the gravitational recoil velocity imparted to the remnant BH, and of the final spin value of the remnant. Given that the magnitude of recoil velocities can in certain cases reach and even exceed the escape velocity of the BH's host halo, these findings could have important astrophysical consequences, especially at high redshifts where halo potential wells are shallow. By incorporating the newest numerical

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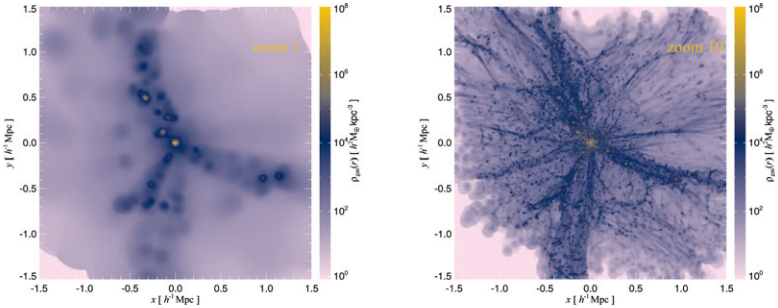

Figure 4. Projected mass-weighted density maps of the most massive halo in the Millennium simulation at $z = 6.2$, resimulated with gas. *Left:* Resimulation performed at the same resolution as the parent Millennium run. *Right:* Resimulation of the same cluster performed with 10^3 higher mass resolution.

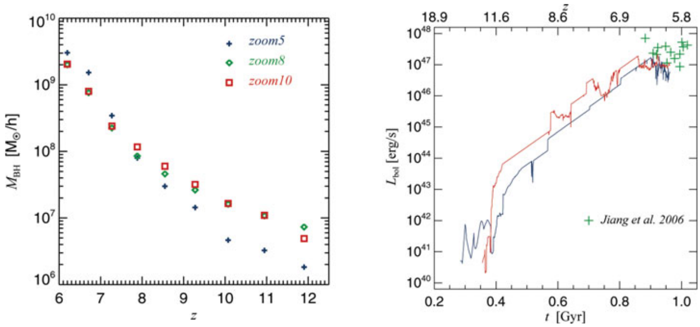

Figure 5. *Left:* The mass of the most massive BH in the simulated volume as a function of redshift for resimulations performed at three different resolutions. *Right:* Bolometric luminosity of the most massive BH in the simulation as a function of redshift (two lines are for runs with different BH seeding prescription). Crosses indicate observational data as indicated in the plot.

relativity results of merging binary BHs in full cosmological simulations, we have explored if indeed gravitational recoils are potential bottlenecks for the assembly of bright quasars (for details see Sijacki *et al.* 2009). While the fraction of expelled BHs can reach up to 40% in some of the adopted scenarios, the most massive BH is very unlikely to get kicked out from its host halo. This is due to the combination of three factors: (i) similar mass mergers which cause high kick velocities are rare for the most massive BH, (ii) the probability of having BH spins oriented in a favorable way to cause high kick velocities is low, and (iii) the most massive BH resides in a relatively massive halo, whose escape velocity is comparatively high.

Another possible bottleneck for the bright quasar assembly could be caused if BHs are rapidly spinning. We have investigated this possibility in full cosmological simulations as well. We fix the initial spin value for all BH seeds and then consider that either (i) BH spins do not change with time, or (ii) BH spins change after BH mergers. In the left-hand panel of Figure 6, we show the mass of the most massive BH assuming different spins and radiative efficiencies, which are kept constant with time. If the BH is rapidly spinning during a large fraction of its assembly, it will not be able to reach $10^9\,M_\odot$ by $z = 6$, in disagreement with observational findings. However, if we relax the condition that spins stay constant (and comparatively high), the BH spin distribution will broaden due to BH mergers (see right-hand panel of Figure 6). Our analysis shows that only BHs which spin rapidly for most of their time and do not experience too many mergers with other

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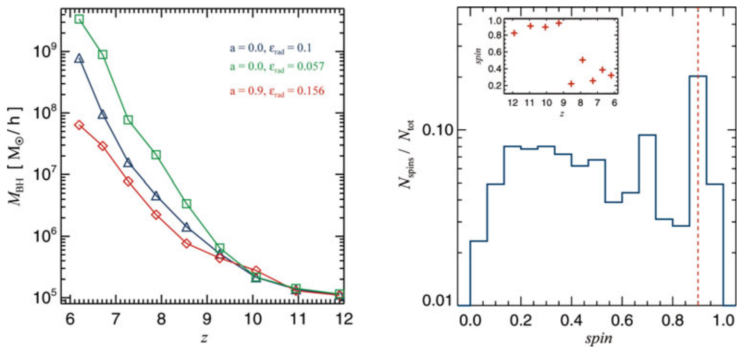

Figure 6. *Left:* The mass of the most massive BH as a function of redshift for runs with different BH spins and radiative efficiencies as indicated in the panel. *Right:* The distribution of BH spins at $z = 6.2$ in the simulation where all BH seeds initially have a spin of 0.9 and spins change due to BH mergers. The spin evolution with time of the most massive BH is shown in the inset.

BHs (and are not spun-down by gas accretion) will have difficulties becoming as massive as bright quasars at $z = 6$.

6. Conclusions

We have shown how a simple yet robust physical model for the co-evolution of BHs and galaxies improves in a number of ways the simulated properties of galaxies, groups and clusters. Moreover, this model accounts for AGN phenomenology over a vast range of redshifts: from bright quasars at $z = 6$ to low activity level radio galaxies in the massive clusters today. These results indicate that BHs are indeed an important ingredient in structure formation processes. However, we should bear in mind that our theoretical understanding of BH growth and feedback is still far from complete. Future observational efforts combined with more sophisticated numerical simulations are the key to understanding in depth the very nature of this remarkable BH–galaxy co-existence.

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