Black hole accretion versus star formation rate: theory confronts observations

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ABSTRACT
We use a suite of hydrodynamical simulations of galaxy mergers to compare star formation rate (SFR) and black hole accretion rate (BHAR) for galaxies before the interaction (‘stochastic’ phase), during the ‘merger’ proper, lasting ∼ 0.2 – 0.3 Gyr, and in the ‘remnant’ phase. We calculate the bi-variate distribution of SFR and BHAR and define the regions in the SFR-BHAR plane that the three phases occupy. No strong correlation between BHAR and galaxy-wide SFR is found. A possible exception are galaxies with the highest SFR and the highest BHAR. We also bin the data in the same way used in several observational studies, by either measuring the mean SFR for AGN in different luminosity bins, or the mean BHAR for galaxies in bins of SFR. We find that the apparent contradiction or SFR versus BHAR for observed samples of AGN and star forming galaxies is actually caused by binning effects. The two types of samples use different projections of the full bi-variate distribution, and the full information would lead to unambiguous interpretation. We also find that a galaxy can be classified as AGN-dominated up to 1.5 Gyr after the merger-driven starburst took place. Our study is consistent with the suggestion that most low-luminosity AGN hosts do not show morphological disturbances.

Key words: galaxies: active – galaxies: interactions – galaxies: nuclei

1 INTRODUCTION

The correlation (or lack thereof) between the black hole accretion rate (BHAR) and the star formation rate (SFR) of their host galaxies has been the subject of numerous investigations (e.g., Netzer 2009; Mullaney et al. 2012b; Rosario et al. 2012; Harrison et al. 2012; Rosario et al. 2013b; Netzer et al. 2014; Hickox et al. 2014, and references therein). One of the drivers behind these studies is the empirical correlation between BH mass and bulge mass in the local universe (Marconi & Hunt 2003; Häring & Rix 2004; Gültekin et al. 2009; Kormendy & Ho 2013) which suggests that the BH and stellar bulge have assembled in tandem (co-evolution). In the strictest view of co-evolution, to obtain a BH mass proportional to the bulge mass, BHAR should be proportional to SFR (or, at least, the SFR that builds-up the bulge). Indeed, the cosmic total SFR and BHAR (i.e., the rate per unit comoving volume) seem to track each other at least to z ∼ 3 (Heckman et al. 2004; Merloni et al. 2004; Silverman et al. 2008, 2009; Madau & Dickinson 2014). A major challenge is to follow the growth for various mass groups separately. This calls for a major observational effort and theoretical investigations needed to interpret them.

When SFR and BHAR are compared source by source, the connection appears to be weak, unless only the SFR in the central region is taken into account (< 1 kpc, Diamond-Stanic & Rieke 2012, and references therein). A comprehensive work of this type by Rosario et al. (2012) shows that at low AGN luminosities, BHAR and SFR are uncorrelated, while at high AGN luminosities a significant correlation emerges. On the other hand, Mullaney et al. (2012) and Chen et al. (2013) study a sample of mass-selected and star-forming galaxies respectively and suggest that the average BHAR correlates well with the average
SFR, once the shorter variability time scales of BHAR with respect to SFR are taken into account (see also Hickox et al. 2014).

In a companion paper (Volonteri et al. 2015) we have used new simulations of galaxy mergers and investigated the temporal correlation between SFR and BHAR, and their respective variability. We found that BHAR and nuclear (< 100 pc) SFR are well correlated and vary on similar timescales. However, we found that galaxy-wide (< 5 kpc) SFR, which is used in statistical studies (Rosario et al. 2012, Mullaney et al. 2012, Chen et al. 2013, Delvecchio et al. 2013), and BHAR are typically temporally uncorrelated, and have different variability timescales, except during the short-lived merger proper (~ 0.2 – 0.3 Gyr).

While the shorter AGN variability explains why the average BHAR correlates with the average SFR, but not source by source, it does not explain why samples that start from an AGN selection by their X-ray properties (e.g., Rosario et al. 2012) find different trends with respect to samples that start from near- or far-infrared selection of galaxies (e.g., Mullaney et al. 2012, Chen et al. 2013, Delvecchio et al. 2015). We here compare SFR and BHAR by referring to the luminosity resulting from these processes (L_{SFR} and L_{AGN} respectively), and aim at providing a framework for comparison with observations.

In this Letter we show how very detailed numerical simulation of galaxy mergers confirm the recent observational finding, provided the simulation results are treated in the same way as observations. In particular we show that accounting for the different durations of the various stages of the mergers, and binning the results in a way similar to the observational methods, can bring the results very close to the observed correlations and reconcile seemingly conflicting results. In §2 we give a short summary of the full simulations described in Volonteri et al. (2015) which are the bases of the present letter. In §3 we compare our simulations to various observed correlations and in §4 present our conclusions.

2 NUMERICAL SETUP

The results presented here are based on our previous detailed work published in Capelo et al. (2013) and Volonteri et al. (2015). For completeness, we summarise below the more important aspects of the simulations.

Our simulations have very high spatial and temporal resolution (gas mass of ~ 5 × 10^5 M_☉, softening length of 20 pc for gas and 5 pc for the BHs, BH properties output every 0.1 Myr), a large range of initial mass ratios, several orbital configurations, and various gas fractions. The main limitation of our suite is that it does not allow to simulate large galaxies. The resolution we need to resolve nuclear inflows and small-scale dynamics causes each of our mergers to be composed of ~ 10^2 particles, and the entire suite required ~ 10^3 particles and several millions of CPU hours.

We compare the BHAR to the SFR within spheres of 100 pc (SFR_{100pc}) and 5 kpc (SFR_{5kpc}) centred around each BH. These spheres are our proxies for the nucleus and the entire galaxy. We divide each merger into three phases, that we dub ‘stochastic’, ‘merger’ proper, and ‘remnant’. The stochastic phase lasts until the second pericentric passage. During this phase the galaxies behave as they do in isolation.

The merger phase starts at the second pericentre, when the specific angular momentum drops abruptly. This phase ends when the specific angular momentum returns to be constant in time. The remnant phase lasts from this moment until the end of the simulation.

The numerical setup includes a suite of hydrodynamical simulations applied to mergers of disc galaxies with mass ratios of 1:1, 1:2, 1:4, 1:6, and 1:10. The chosen redshift, z = 3, corresponds to the peak of the cosmic merger rate. Details on the numerical implementation of galaxies and BHs are presented in Capelo et al. (2015) and Volonteri et al. (2015), where tables detailing all the simulations can be found. We chose an orbital configuration that matches those of the most common halo mergers in cosmological simulations of galaxy formation (Benson 2003, Khochfar & Burkert 2006). We set the initial pericentre distance near 20 percent of the virial radius of the larger galaxy, and the initial separation between the galaxies is set near the sum of the two virial radii. We consider coplanar, prograde-prograde mergers, inclined mergers, and coplanar, retrograde mergers.

All galaxies are composite systems of dark matter, gas, stars, and a central BH. The dark matter halo is described by a spherical Navarro-Frenk-White profile (Navarro et al. 1997). The disc has an exponential density profile with total mass equal to 4 percent of the virial mass of the galaxy, and a gas fraction of f_{gas} = 0.3 or f_{gas} = 0.6. The stellar bulge is described by a spherical Hernquist (1990) density profile with total mass equal to 0.8 percent of the virial mass of the galaxy. The larger galaxy has a virial mass of 2.24 × 10^{11} M_☉. Stellar and gas particles initially have the same particle mass (3.3 × 10^{5} and 4.6 × 10^{5} M_☉), respectively and softening length (10 and 20 pc, respectively). Each galaxy is initialized with a uniform stellar population with an age of 2 Gyr to reflect the young age of the Universe at z = 3.

We performed our simulations using the N-body SPH code GASOLINE (Wadsley et al. 2004), an extension of the pure gravity tree code PKDGRAV (Stadel 2001). GASOLINE includes explicit line cooling for atomic hydrogen, helium and metals, as well as a physically motivated prescription for SF, supernova feedback and stellar winds (Stinson et al. 2004). Data on SFR is extracted every 1 Myr. BHs are implemented as sink particles that accrete from nearby gas particles according to a Bondi–Hoyle–Littleton accretion formula. The accretion rate is computed as the sum of the Bondi accretion rate of each individual gas particle near the BH, including the relative velocity with respect to the BH, rather than simply averaging the gas quantities over all the neighboring particles. BH feedback is implemented as thermal energy injected into the nearest gas particle according to $E = \epsilon f M_{\text{BH}} c^2$, where $c$ is the speed of light in vacuum, $\epsilon_f = 0.1$ is the radiative efficiency and $\epsilon$ is the AGN feedback efficiency, chosen to be equal to 0.001 to match the local M_{BH}–M_{bulge} relation over the galaxy evolution. We place a single BH at the centre of each galaxy, after the galaxy has been initialized with mass in accord with the local BH–mass to bulge ratio (M_{BH} = 2 × 10^{-3} M_{bulge}) (Marconi & Hunt 2003). The softening length of all BHs is set to 5 pc, regardless of their mass.
3 COMPARISON WITH OBSERVATIONS

The comparison of the numerical simulations with observed correlations has some caveats. As discussed by Neistein & Netzer (2014), measurements of SFRs are based on indicators that last $\gtrsim 100$ Myr, while the AGN luminosity, hence the BHAR, is measured instantaneously. Because of this, all our results concerning SFR represent averages over 100 Myr. The SFR is converted to SF luminosity, $L_{\text{SFR}}$, by assuming that one solar mass per year corresponds to $10^{10}$ solar luminosities. BHAR is averaged instead over 1 Myr (see Volonteri et al. 2015 for a case where BHAR and SFR are measured over the same time interval). We distinguish between SF dominated galaxies ($L_{\text{SF}} > L_{\text{AGN}}$) and AGN dominated galaxies ($L_{\text{SF}} < L_{\text{AGN}}$).

An additional important difference between theory and observations is related to the fact that observed samples do not contain information about the fraction of sources in the stochastic, merger and remnant stages, and how many represent 1:2, 1:6 or 1:10 mass ratio systems. As shown in Fig. 1, the three stages of the mergers cover differently the SFR-BHAR plane and a proper comparison with the observations requires an adjustment of the various numbers in the three groups.

The approach we adopt is to specify the boundaries of a region in the BHAR-SFR plane relevant to a population of relatively low-mass galaxies that includes quiescent galaxies and mergers with mass ratio from 1:1 to 1:10. Real correlations depend on the distribution of points within these boundaries, and will include galaxies of different masses and structural parameters, and this we cannot do quantitatively. One can, however, estimate the fraction of objects in each of the merger phases that is included in most observed samples, e.g., the remnant phase in low-redshift samples, and remnants+mergers in higher-redshift samples. The duration of each phase must also be taken into account, since this determines the number of objects from this phase in a specific sample and hence the nature of the derived correlations that depend on such numbers. For example, the merger phase, being short-lived, $\sim 0.2 - 0.3$ Gyr, is sub-dominant in the general distribution, with respect to the stochastic and remnant phases, which last $0.8 - 1.3$ Gyr each.

3.1 Bi-variate distribution

In Fig. 1 we show the bi-variate distribution of BHAR and SFR within 100 pc, and within 5 kpc, distinguishing galaxies in the stochastic (red), merger (gold) and remnant (dark gray) phases. In the case of the central SFR, $SFR_{100pc}$ (left panel), the stochastic and remnant phases occupy similar regions, while the merger phase, beyond a primary peak coincident with the other two phases, presents a secondary peak at higher BHAR and $SFR_{100pc}$. The secondary peak is limited in its extent in SFR because averaging over 100 Myr removes the highest peaks of SFR, which are associated to the highest peaks in BHAR (cf. Fig. 14 in Volonteri et al. 2015). As noted previously (Hopkins & Quataert 2010; Thacker et al. 2011; Diamond-Stanic & Rieke 2012), $SFR_{100pc}$ is a better tracer of BHAR than $SFR_{5kpc}$, i.e., they are better correlated. As discussed by Capelo et al. 2015 (see also Hopkins & Quataert 2010), the main drivers of the BHAR are the gas content (setting mostly an overall ‘normalisation’, see also Rosario et al. 2013; Vito et al. 2014) and local losses of angular momentum.

The link between galaxy-wide SFR ($SFR_{5kpc}$, right) and BHAR seems much weaker. Galaxies in the stochastic phase
occupy a region in the BHAR-SFR$_{5\text{kpc}}$ plane (red contours in Fig. [1] roughly tracing the region between the relations suggested by Mullaney et al. 2012 and Chen et al. 2013 to characterise star-forming galaxies (dotted blue lines). The merging systems (gold contours) approach the upper part of the curves shown in Rosario et al. (2012) for a large sample of AGN, who suggest that the highest luminosity AGN are merger-driven, and they exhibit a tighter correlation between BHAR and SFR$_{5\text{kpc}}$. In fact, in the merger phase, losses of angular momentum are driven by global dynamics and BHAR and SFR become somewhat better correlated even on large scales. In the remnant phase (gray contours) a wide range of BHAR can be associated to a given SFR$_{5\text{kpc}}$.

The remnant phase is, perhaps, the most interesting when comparing to AGN observations, as 80 percent of the AGN do not show any hint of a companion (e.g., Rosario et al. 2012) and are ordinary (massive) star forming galaxies. For most of the remnant phase the simulated galaxies do not show strong morphological disturbances, however, the BHAR is sufficiently high at times that the galaxies enter the AGN dominated region of the BHAR-SFR$_{5\text{kpc}}$ diagram. Observationally, this has been a matter of some debate. Rosario et al. (2013) find a strong connection between AGN activity and SFR, i.e. most AGN hosts are on the main-sequence of star forming galaxies (Elbaz et al. 2007; Noeske et al. 2007). It has been suggested that there is an excess of AGN in post-merger (Ellison et al. 2013) or post-starburst galaxies (Wild et al. 2010), and that galaxies hosting moderate-luminosity AGN are transitioning from SF to quiescence (Schawinski et al. 2009), suggesting that the starburst precedes BH accretion. Our broad interpretation is that the AGN is more likely to be observed in the (much longer) remnant phase, where it enters the AGN-dominated region. In fact, in our calculations (Fig 13 in Volonteri et al 2015), the AGN zigzags continuously in and out of this region.

We can now estimate the fraction of galaxies in different stages of the merger that are likely to be found in large observed samples. According to our calculations (see also Volonteri et al. 2015), galaxies in the merger phase would be considered AGN-dominated ($L_{\text{AGN}} > L_{\text{SFR}}$) for about 40 per cent of that phase, galaxies in the remnant phase are AGN-dominated for 25 per cent of their phase, and galaxies in the stochastic phase 7 per cent. However, the merger phase is much shorter than the stochastic and remnant ones. Therefore the overall probability, defined as the ratio between the time when $L_{\text{AGN}} > L_{\text{SFR}}$ and the total simulation time (stochastic + merger + remnant), of finding a galaxy in the remnant phase in the AGN-dominated region is almost twice as large than for a merging galaxy (13 per cent versus 7 per cent respectively), and six times higher than for a galaxy in the stochastic phase.

### 3.2 BHAR versus SFR using binned data

Most observational papers do not consider the full bi-variate distribution of SFR and BHAR (Fig. 1). Instead, they focus on the mean SFR for AGN in different luminosity bins (i.e. stacking galaxies in bins of BHAR; e.g., Rosario et al. 2012) or the mean BHAR in SFR bins (i.e. stacking galaxies in bins of SFR; e.g., Mullaney et al. 2012, Chen et al. 2013 and Delvecchio et al. 2015). To compare our simulations with those observations, we binned our simulated galaxies exactly in the same way as used in the observations: i.e., we calculate the mean SFR in bins of BHAR and the mean BHAR in bins of SFR. The results are shown in Fig 2 where the first way of binning is shown in the top panel and the second in the bottom panel. Remarkably, in the former case we recover the trends of Rosario et al. (2012), while in the latter we recover the trend found by Mullaney et al. (2012), Chen et al. (2013) and Delvecchio et al. (2015) in their different redshift samples. We suggest that the different trends found for AGN and SF galaxies in the aforementioned papers are caused by the different projections of the full bi-variate distribution, and that the intrinsic distribution of properties in those samples is similar to the one shown in Fig. 1.

Note, again, that our simulations apply only to small- to medium stellar mass systems. We can try to extrapolate the behaviour to more massive galaxies using the arguments outlined in Volonteri et al. 2015, that are based on the assumption that both BHAR and SFR would increase approximately linearly with stellar mass. In this case, larger galaxies would move by about one order of magnitude of BHAR per one order of magnitude of SFR in the plane shown in Fig. 1. This leads us to suggest that if our stellar masses and BHs were two orders of magnitude larger (a few times $10^{12}$ and $10^{8}$ solar masses respectively) then, during the merger and remnant phases, they would occupy a region surrounding the $z = 2$ curve of Rosario et al. (2012) when we bin in BHAR. A shift of 0.5 dex in mass, i.e. in both BHAR and SFR, would bring our galaxies to the $z = 0.5 - 0.8$ curve shown in this paper (the shapes of all these curves in Rosario et al. 2012 are basically identical). The mean for the entire population is close to the gold points in the top panel.
of Fig 2. This does not mean that the average is dominated by merging systems: the merger phase is short-lived, therefore most galaxies in an ensemble would be either in the stochastic or the remnant phase and the population average is a combination of galaxies in the two phases.

In the case of binning in SFR (lower panel of Fig. 2), simulated galaxies in the merger and remnant phases are ~ 0.5 – 1 dex above the extrapolation of the relation suggested by Mullaney et al. (2012) and Chen et al. (2013), and above the points by Delvecchio et al. (2015) with L(2–10 kev) > 10^{41} erg s^{-1}. However, galaxies in the stochastic phase are closer to the observed correlation. Furthermore, if we select only SF-dominated galaxies (LSF > L_{AGN}), the simulations would sit on the curve proposed by Mullaney et al. (2012).

4 CONCLUSIONS

We analyse a suite of high-resolution galaxy merger simulations and use them to study BH and galaxy properties during various phases of the mergers. We calculate the BHAR and the SFR during the ‘stochastic’ phase (corresponding to a galaxy in isolation or in the early phases of an encounter), the ‘merger’ proper (when the merger dynamics dominates), and the ‘remnant’ phase (from the end of the merger to the return to quiescence). The main goal in this Letter is to compare the predicted relationships between BHAR and SFR with observations.

The major result is that we are able to reconcile seemingly contradictory observational results by noting that the observational studies do not consider the full bi-variate distribution of SFR and BHAR, but rather measure the mean SFR for AGN in different luminosity bins (e.g., Rosario et al. 2012) or the mean BHAR stacking galaxies in bins of SFR (e.g., Mullaney et al. 2012, Chen et al. 2013, Delvecchio et al. 2015). Using different projections of the bi-variate distribution recovers different observed trends of the population.

The bi-variate distribution derived from our simulations suggests that galaxies in the stochastic phase would not be considered AGN-dominated (LSF > L_{AGN}). Galaxies would be considered AGN-dominated chiefly during the merger and remnant phases. During most of the merger proper and in the remnant phase no correlation between BHAR and global SFR is found, as a given SFR can be associated with a large range of BHAR. A possible exception is the groups of galaxies with the highest SFR and the highest BHAR, characterised by having LSF ≃ L_{AGN}.

Finally, we find that in the remnant phase, up to 1.5 Gyr after the main starburst took place, the BHAR can be sufficiently high at times to move the galaxy into the AGN dominated region, and the probability of finding a galaxy in the remnant phase, even long after the starburst took place, in the AGN-dominated region is twice as large than for a merging galaxy.

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