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Black hole spin and radio loudness in a Λ cold dark matter universe

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ABSTRACT

We use a combination of a cosmological *N*-body simulation of the concordance Λ cold dark matter paradigm and a semi-analytic model of galaxy formation to investigate the spin development of central supermassive black holes (BHs) and its relation to the BH host galaxy properties. In order to compute BH spins, we use the α model of Shakura & Sunyaev and consider the King et al. warped disc alignment criterion. The orientation of the accretion disc is inferred from the angular momentum of the source of accreted material, which bears a close relationship to the large-scale structure in the simulation. We find that the final BH spin depends almost exclusively on the accretion history and only weakly on the warped disc alignment. The main mechanisms of BH spin-up are found to be gas cooling processes and disc instabilities, a result that is only partially compatible with Monte Carlo models where the main spin-up mechanisms are major mergers and disc instabilities; the latter results are reproduced when implementing randomly oriented accretion discs in our model. Regarding the BH population, we find that more massive BHs, which are hosted by massive ellipticals, have higher spin values than less massive BHs, hosted by spiral galaxies. We analyse whether gas accretion rates and BH spins can be used as tracers of the radio loudness of active galactic nuclei (AGN). We find that the current observational indications of an increasing trend of radio-loud AGN fractions with stellar and BH mass can be easily obtained when placing lower limits on the BH spin, with a minimum influence from limits on the accretion rates; a model with random accretion disc orientations is unable to reproduce this trend. Our results favour a scenario where the BH spin is a key parameter to separate the radio-loud and radio-quiet galaxy populations.

Key words: galaxies: active – galaxies: evolution.

1 INTRODUCTION

Galaxies with active galactic nuclei (AGN) have become the centre of attention in extragalactic studies due to their star role in the galaxy formation scenario favoured today. They are a key ingredient in explaining several observational statistics on galaxy star formation rates, luminosities and colours (see for instance Bower et al. 2006; Cattaneo et al. 2006; Croton et al. 2006; Sijacki et al. 2007; Lagos, Cora & Padilla 2008; Marulli et al. 2008; Somerville et al. 2008). However, a number of phenomena related to AGN are still unclear, including the origin of the AGN dichotomy into 'radio-loud' (RL) and 'radio-quiet' (RQ) types. RL AGN are characterized by the presence of jets of relativistic plasma and/or associated large-scale radio lobes. Relativistic jets emitting synchrotron radiation in the radio band are generated by the collimation of outflows from the innermost regions of accretion discs around black holes (BHs), carrying away a large fraction of the available accretion power. However, the jet production mechanism is not fully understood. The double-lobed morphology Fanaroff & Riley (1974) Class II (FR II) sources are the most common type observed in broad-line emitting RL quasars. On the other hand, the lower luminosity Fanaroff & Riley Class I (FR I) objects have very weak radio emitting ejecta and weak or no emission lines. The correlation between radio luminosity and line luminosity in [O III] λ5007 is similar for both RL and RQ AGN (Xu, Livio & Baum 1999).

Different criteria for the definition of radio loudness have been used, the most common being the ratio between radio-to-optical luminosity, $\mathcal{R}$ (Kellermann et al. 1989), and the radio power (Miller et al. 1990). A third criterion based on the classical radio morphology has also been considered (Sulentic et al. 2003). From the combination of the two latter criteria, Zamfir, Sulentic &

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Marziani (2008) find that the boundary between RL and RQ AGN is given by $\log L_{1.4\,\mathrm{GHz}} = 31.6\,\mathrm{erg\,s^{-1}\,Hz^{-1}}$, which corresponds to the luminosity of the weakest FR II sources. Using this luminosity threshold, they obtain a fraction of ∼5–9 per cent of RL AGN relative to the total population of AGN. The presence of a physical bimodality in the properties of AGN is still a matter of debate, and it should be borne in mind that observational selections might actually induce this dichotomy (e.g. Cirasuolo et al. 2003; White et al. 2007).

The host galaxies of both RL and RQ quasi-stellar objects (QSOs) with nuclear luminosities $M_V < -24$ are massive ellipticals (Dunlop et al. 2003; Floyd et al. 2004); disc-dominated host galaxies become increasingly rare as the nuclear power increases. Sikora, Stawarz & Lasota (2007) demonstrate that radio-selected AGN hosted by giant ellipticals can be up to a thousand times brighter in radio frequencies than AGN hosted by disc galaxies, thus generating two sequences in the radio versus optical luminosity plane. These RL and RQ sequences remain present when considering the dependence of the radio loudness $\mathcal{R}$ with the Eddington ratio, where the latter is defined as the bolometric luminosity (estimated from optical data) in units of the Eddington luminosity. The two sequences show an increase of radio loudness with decreasing Eddington ratio. This bimodality breaks down at high accretion rates. This behaviour was originally noted by Ho (2002), although only a single sequence was visible as a consequence of the reduced sample of AGN considered.

The link between jet production and gas accretion rate on to the BH has been widely investigated. The inner part of the accretion flow is believed to be responsible for the observed hard X-ray emission produced by the Compton scattering or by the Bremsstrahlung radiation. Thus, observations of the compact emission in the X-ray and radio bands help us understand the disc-jet connection in both stellar and supermassive BHs (Ulvestad & Ho 2001; Merloni, Heinz & di Matteo 2003; Falke, Körding & Markoff 2004; Körding, Jester & Fender 2006), under the assumption that the jet formation process is qualitatively similar on both scales. Observations of BH binary systems during the low/hard X-ray state reveal a tight correlation between the radio and X-ray luminosity (Gallo, Fender & Pooley 2003), supporting the dependence of the radio power on the accretion rate. This 'accretion paradigm' postulates that radio loudness is entirely related to the states of accretion discs. However, it cannot explain the two parallel sequences that AGN occupy in the plane defined by radio loudness and the Eddington ratio, as found by Sikora et al. (2007). Hence, it is possible that additional BH properties could be playing an important role in driving the production of powerful relativistic radio jets.

The RL and RQ sequences found by Sikora et al. (2007) are characterized by AGN containing BHs with masses $\gtrsim 10^8$ and $\lesssim 3 \times 10^7\,\mathrm{M_\odot}$, respectively. None the less, the BH mass is not capable of completely separating these two sequences, since objects powered by equally massive BHs can differ in radio luminosity by ∼4 orders of magnitude (Ho 2002; Dunlop et al. 2003; Sikora et al. 2007). Blandford (1990) introduces a new parameter suggesting that the efficiency of jet production is determined by the dimensionless BH spin, according to the assumption that relativistic jets are powered by rotating BHs through the Blandford–Znajek mechanism. In an attempt to explain this radio power dichotomy at fixed accretion rates, Sikora et al. (2007) propose a revised version of the 'spin paradigm' which suggests that giant elliptical galaxies host, on average, BHs with larger spins than those hosted by spiral galaxies. These new insights inferred from observational evidences motivated the study of the influence from BH mergers and small accretion episodes on the evolution of BH spins and their relation to the morphology of the host galaxy (e.g. Nemmen et al. 2007; Volonteri, Sikora & Lasota 2007; Berti & Volonteri 2008). These theoretical works indicate that it is feasible that the observed morphology-related bimodality of AGN radio loudness arises from the dichotomy shown by the distribution of BH spins.

In this paper, we investigate the latter possibility by using the Semi-Analytic Galaxies (SAG) semi-analytic model of galaxy formation by Lagos et al. (2008, hereafter LCP08), combined with the outputs of a cosmological simulation based on the Λ cold dark matter (ΛCDM) cosmology. The advantage of this approach relies in that we are able to use realistic BH growth histories directly linked to the evolution of the star formation rate of their host galaxies. The SAG model also allows us to evaluate the influence of the different mechanisms that contribute to the accretion of material on to the BHs, which drive both the BH mass growth and the BH spin development.

This work is organized as follows. In Section 2, we briefly summarize the mechanisms that contribute to the BH growth included in SAG, and describe in detail the implementation of the BH spin model. In Section 3, we discuss the connection between the BH spin distributions and the characteristics of the BH host galaxies. Section 4 shows the results on the final BH spin and the way in which it is acquired. In Section 5, we analyse the nature of AGN radio loudness and compare our results with available observational data. Finally, the main conclusions obtained in this work are summarized in Section 6.

2 COMPUTING THE BLACK HOLE SPIN

We study the relationship between the BH spin and the properties of the BH host galaxy using a combination of a cosmological *N*-body simulation of the concordance ΛCDM universe and the SAG semi-analytic model of galaxy formation described in LCP08. This model considers radiative cooling of hot gas, star formation, galaxy mergers, disc instabilities, feedback from supernova explosions, BH growth and AGN feedback produced during accretion on to BHs driven by gas cooling processes.

In the following sections, we briefly describe the *N*-body cosmological simulation and the BH growth model used in SAG, relevant for this study. We then explain in detail the implementation of the model to compute the BH spin.

2.1 ΛCDM cosmological simulation

The cosmological simulation is the same as the one used by LCP08, based on the concordance ΛCDM cosmology. It considers a periodic box of $60\,h^{-1}$ Mpc containing 16, 777 and 216 dark matter particles with mass $1.001 \times 10^9\,h^{-1}\,\mathrm{M_\odot}$. It has more than 54 000 dark matter haloes with masses of up to $5.36 \times 10^{14}\,h^{-1}\,\mathrm{M_\odot}$. The simulation parameters are consistent with the results of *Wilkinson Microwave Anisotropy Probe* data (Spergel et al. 2003), with $\Omega_\mathrm{m} = \Omega_\mathrm{DM} + \Omega_\mathrm{baryons} = 0.28$ (with a baryon fraction of 0.16), $\Omega_\Lambda = 0.72$ and $\sigma_8 = 0.9$. The Hubble constant is set to $H_0 = 100\,h\,\mathrm{Mpc}^{-1}$, with $h = 0.72$, and the gravitational softening length is $\epsilon = 3.0\,h^{-1}$ Kpc. The simulation starts from a redshift $z = 48$ and has been run using the public version of the GADGET-2 code (Springel 2005).

2.2 BH growth

There are three distinct modes of BH growth in SAG. The first one, referred to as the 'QSO mode', is associated with starbursts in galaxies. These events can be driven by galaxy minor or major mergers and the collapse of unstable discs. The second one, referred to as the 'radio mode', is associated with gas cooling processes that produce star formation in a more quiescent way. The third one is BH mergers which occur shortly after the merger of the parent galaxies. In our model, the AGN feedback occurs only during the latter mode which produces low accretion rates, in agreement with observations (e.g. Ho 2002; Donahue et al. 2005; Sikora et al. 2007). The detailed assumptions for each mechanism are given in LCP08. Here, we briefly describe the main formulae involved.

During galaxy mergers, the BH growth depends on the ratio between total galaxy mass and the amount of available cold gas (Croton et al. 2006, LCP08) as

$$\dot{M}_{\rm BH} = \frac{f_{\rm BH}}{\Delta t}\frac{M^{\rm sat}}{M^{\rm central}} \times \frac{M_{\rm ColdGas}}{1+(200\,{\rm km\,s^{-1}}/V_{\rm vir})^2}, \quad (1)$$

where $M_{\rm ColdGas}$ is the cold gas mass of the system, consisting of the central and satellite galaxies, with masses (including stellar and cold gas mass) $M^{\rm sat}$ and $M^{\rm central}$, respectively; Δt is the time-scale between consecutive SAG time-steps. BHs are assumed to grow with an efficiency $f_{\rm BH} = 0.015$, set to fit the $M_{\rm BH}$–$M_{\rm Bulge}$ relation. For disc instabilities, the ratio $M^{\rm sat}/M^{\rm central}$ is replaced by unity, since this process depends on the properties of a single galaxy. It is important to note that there are no BH seeds in our model and, therefore, the birth of central supermassive BHs is triggered when galaxies undergo their first starburst at some point in their evolution.

The accretion rate during the 'radio mode' is given by

$$\dot{M}_{\rm BH} = \kappa_{\rm AGN}\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot} \times \frac{f_{\rm hot}}{0.1} \times \left(\frac{V_{\rm vir}}{200\,{\rm km\,s^{-1}}}\right)^3, \quad (2)$$

where $M_{\rm BH}$ is the BH mass and $f_{\rm hot}$ is the fraction of the total halo mass in the form of hot gas, $f_{\rm hot} = m_{\rm HotGas}/M_{\rm vir}$, $M_{\rm vir}$ being the virial mass of the host halo which has a virial velocity $V_{\rm vir}$ and $\kappa_{\rm AGN}$ is a free parameter set to fit the galaxy and QSO luminosity functions with a value $2.5 \times 10^{-4}\,{\rm M}_\odot\,{\rm yr}^{-1}$.

Irrespective of the accretion mode, the BH produces a luminosity that corresponds to the total release of energy from the disc formed by gas accretion. This luminosity is given by $L_{\rm BH} = \eta\,\dot{M}_{\rm BH}c^2$, where c is the speed of light and $\eta = 0.1$ is the standard efficiency of energy production that occurs in the vicinity of the event horizon (Shakura & Sunyaev 1973, hereafter SS73).

2.3 BH spin

Our implementation of a BH spin model in SAG follows the same methodology adopted for all the galaxy properties considered in the semi-analytic model, which consists in solving a set of linearized differential equations. The BH spin in each galaxy is followed through the evolutionary history of the simulated universe, allowing us to analyse the way in which the BH spin is acquired for every host galaxy and to study directly the role and influence of the hierarchical buildup of structure in the development of this BH property. During galaxy mergers, the two central supermassive BHs are also merged; we simply consider that the mass of the final BH is the sum of the merging BH masses; the resulting spin is calculated using the semi-analytic fitting formulae presented by Rezzolla et al. (2008) to fit a complete compilation of numerical results on BH mergers. The other processes involved in the BH growth feed baryons through the formation of accretion discs. The treatment of the angular momentum transfer from the accretion disc to the BH requires the following analysis.

The dimensionless BH spin is defined as $\hat{a} \equiv J_{\rm BH}/J_{\rm MAX} = cJ_{\rm BH}/GM^2_{\rm BH}$, where $J_{\rm BH}$ is the angular momentum of the BH. In general, J refers to the absolute value of the angular momentum, $|\boldsymbol{J}|$. We consider the presence of a warped disc characterized by the angular momentum of the accretion disc at the warp radius, $J_{\rm d} = J_{\rm d}(R_w)$ (Volonteri et al. 2007). In this case, the amount $J_{\rm d}/J_{\rm BH}$ can be used to define the alignment between the spinning BH and the accretion disc (King et al. 2005, hereafter K05). Angular momentum vectors are co-aligned when $\cos(\phi) > -0.5J_{\rm d}/J_{\rm BH}$, ϕ being the angle between the disc angular momentum and the BH spin; otherwise, the accretion disc is counter-aligned with the BH spin. We use this criterion to evaluate the BH spin-up or spin-down in the presence of a warped disc.

SAG does not assume an initial mass for BHs, or BH seeds; instead, the first starburst in a galaxy, that occurs during galaxy mergers or disc instabilities, creates the central BH. These processes would therefore be in line with an origin of supermassive BHs as remnants of the first events of stellar explosions early in the history of the Universe (e.g. Shapiro 2005; Bernadetta & Volonteri 2008; Elmegreen, Bournaud & Elmegreen 2008; Omukai, Schneider & Haiman 2008). Given this possible stellar origin of the BHs, it is reasonable to expect their initial spin to be non-zero. However, for the sake of completeness, we also study the effect of initially spinless BHs, which could be formed by rapid collapse of infalling gas (see for instance Begelman, Volonteri & Rees 2006). In this latter case, BHs acquire spin for the first time during their first accretion episode or merger with other BH. In the case of an accretion event, the resulting spin is given by the formalism developed by Bardeen (1970). When two spinless BHs merge, we use the analytic formula given by Berti & Volonteri (2008); when at least one merging BH has a non-zero spin, the resulting spin is calculated using the semi-analytic fitting formulae presented by Rezzolla et al. (2008) to fit a complete compilation of numerical results on BH mergers.

In the case of BHs with non-zero spin, we calculate $J_{\rm d}$ taking into account the mass of the accretion disc, $M_{\rm d}$, and the remaining properties related to the BH, $M_{\rm BH}$, $\dot{M}_{\rm BH}$ and $L_{\rm BH}$; all these quantities are provided by the SAG model. The ratio between the angular momentum of the accretion disc and the BH spin is expressed as

$$\frac{J_{\rm d}}{J_{\rm BH}} = \frac{M_{\rm d}}{\hat{a}M_{\rm BH}}\left(\frac{R_w}{R_{\rm s}}\right)^{1/2}, \quad (3)$$

where $M_{\rm d} = \dot{M}_{\rm BH}\Delta t$. The accretion rate $\dot{M}_{\rm BH}$ comes either from equation (1) or (2). Accretion discs are completely consumed in the time interval $\Delta\ t$. The ratio $R_w/R_{\rm s}$ is the warp radius expressed in terms of the Schwarzschild radius, $R_{\rm s}$; in a SS73 middle-region disc, this ratio can be written as

$$\frac{R_w}{R_{\rm s}} = 3.6\times10^3\hat{a}^{5/8}\left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^{1/8} f_{\rm Edd}^{-1/4}\left(\frac{\nu_2}{\nu_1}\right)^{-5/8}\alpha^{-1/2} \quad (4)$$

(e.g. K05, Volonteri et al. 2005), where $f_{\rm Edd} \equiv L_{\rm BH}/L_{\rm Edd}$, $L_{\rm Edd}$ being the Eddington luminosity, ν_2 the warp propagation viscosity and ν_1 the accretion driving viscosity (ν_2 can be different from ν_1). The parameter α, introduced by SS73, takes into account the efficiency of the mechanism of angular momentum transport. A thin accretion disc is characterized by $H/R < \alpha \ll 1$, where H and R are the disc thickness and radius, respectively. In this case, it can be shown that $\nu_2/\nu_1 \approx \alpha^2$ (Papaloizou & Pringle 1983). None the less, at high accretion rates (i.e. hot/thick accretion discs) there are indications that $\alpha \gtrsim 0.1$ (e.g. Dubus, Hameury & Lasota 2001). Based on these theoretical and observational indications, we adopt simple criteria to distinguish between thin and thick accretion discs and, therefore, to choose an appropriate value for α.

(i) *Thick accretion disc*: if the accretion occurs at super-Eddington rates, i.e. $L_{\rm BH}/L_{\rm Edd} > 1$, the accretion proceeds via a radiation pressure supported thick disc with $H \sim R$ (e.g. Volonteri et al. 2005; Begelman et al. 2006), which implies $\nu_1 \approx \nu_2$ (e.g. Kumar & Pringle 1985) and $\alpha \gtrsim 0.1$ (e.g. Dubus et al. 2001).

(ii) *Thin accretion disc*: if the accretion occurs in the regime of $L_{\rm BH}/L_{\rm Edd} < 1$, it is assumed that $H/R \sim \alpha \ll 1$.

In order to test the reliability of our results, we adopt different values of the parameter α ranging from ∼0.1 to ∼0.5 for the thick disc, and from $\sim 10^{-4}$ to ∼0.05 for the thin disc. It is important to remark that the distinction between thick and thin discs has a direct consequence on the amount of angular momentum per unit mass transferred from the accretion disc to the BH, for the same disc mass. This arises from the dependence of equation (4) on the parameter α and on the viscosities ν_1 and ν_2. This is a simplified approach to more sophisticated models which emphasize the importance of the disc thickness (e.g. Hawley & Krolik 2006).

There are a number of works that study in detail the possibility of alignments between galactic-scale structures and the central BH–disc system. Bogdanović, Reynolds & Miller (2007) find indications of co-alignment between the BH spin and large-scale gas flows coming from galaxy mergers. Also, Lindner & Fragile (2007) show that the jet direction is set by the BH angular momentum. These results indicate a possible co-alignment between the jet direction and the angular momentum of the accretion disc of the host galaxy, also supported by observations of high-redshift radio galaxies (Chambers, Miley & van Breugel 1987; Lacy et al. 1999; Inskip et al. 2005). Moreover, Berti & Volonteri (2008) show that high spin values are efficiently achieved by a model with non-chaotic accretion episodes that could explain the very large spin $\hat{a} \approx 0.99$ of the case of MCG-06-30-15 (Brenneman & Reynolds 2006). These arguments make it relevant to consider the possibility that the direction of the angular momentum of the accretion disc is related to the physical process that triggers the gas accretion; this would be possible for short dynamical friction timescales of the infalling gas, to allow the conservation of the original direction.

We test this possibility using the information provided by our model as follows. When the accretion is driven by disc instabilities, we assume that the direction of the accretion disc can be inferred from the angular momentum $\boldsymbol{L}_{\rm Gal,disc}$ of the galaxy disc,

$$\boldsymbol{J_{\rm d}} = J_{\rm d} \times \hat{L}_{\rm Gal,disc}. \qquad (5)$$

On the other hand, if the accretion is driven by gas cooling, we assume that the direction will be that of the angular momentum of the host halo,

$$\boldsymbol{J_{\rm d}} = J_{\rm d} \times \hat{L}_{\rm Halo}. \qquad (6)$$

If the gas accretion is driven by galaxy mergers, the direction is taken from the gas mass-weighted disc angular momentum contributed by each galaxy,

$$\boldsymbol{J_{\rm d}} = J_{\rm d} \times \left(\hat{L}^{\rm central}_{\rm Gal,disc} \times \frac{M^{\rm central}_{\rm ColdGas}}{M_{\rm ColdGas}} + \hat{L}^{\rm sat}_{\rm Gal,disc} \times \frac{M^{\rm sat}_{\rm ColdGas}}{M_{\rm ColdGas}} \right), \qquad (7)$$

where $M^{\rm central}_{\rm ColdGas}$ and $M^{\rm sat}_{\rm ColdGas}$ are the cold gas mass of the central and satellite galaxies, respectively. Having the information on $\boldsymbol{J}_{\rm d}$, we determine the co-(counter-)alignment according to the K05 criteria to finally sum (subtract) $J_{\rm d}$ to $J_{\rm BH}$.

Since a ΛCDM universe is characterized by strong co-alignments between the angular momentum of dark-matter haloes and their surrounding structures on scales of several Mpc (Paz, Stasyszyn & Padilla 2008), there could be some level of alignment between the BH spin and the large-scale structure (LSS). In order to explore this, the initial angular momentum of the gaseous disc of our model galaxies is inferred from that of their host dark-matter haloes. Then, the angular momentum of model galaxies is followed and updated at every star formation episode, which can introduce some degree of misalignment with that of the hosting haloes. In the case of gas cooling processes, we consider that the cooled gas added to the galaxy disc drags the angular momentum of the host halo (Cole et al. 2000), modifying the pre-existing angular momentum of the galaxy disc. During mergers and disc instabilities, the contributions from the participating gas and stellar components are taken into account to obtain the resulting galaxy angular momenta. We also consider randomly oriented accretion events (e.g. King & Pringle 2007; Volonteri et al. 2007) in order to study the main consequences arising from these two possible scenarios.

We also analyse the results obtained from a model where the timescale for disc warping is much longer than for gas accretion. In this case, we ignore the K05 alignment criterion, and the angular momentum of the disc is simply vectorially added to the BH spin. In all cases, the final BH spin direction will be that of the total angular momentum of the system (BH and accretion disc) which is assumed to be conserved. This assumption is not fully accurate since the torque exerted by the accretion disc acting over the total angular momentum of the system may be important (e.g. Volonteri et al. 2005).

Since we are not considering angular momentum losses by torques, our estimates of the values of BH spins are upper limits. In case that the spin takes unphysical values ($\hat{a} > 1$), we simply set them to $\hat{a} = 1$. However, when the resulting spin values are more than half a decade larger than unity, we also reduce the gas accretion on to the BH consistently with this new upper limit. We find that adopting values of $\alpha = 0.5$ for thick discs and $\alpha = 0.05$ for thin discs, only 15 per cent of all accretion events in our model produces values of $\hat{a} > 1$ (only ≈0.1 per cent yields $\hat{a} > 3$). Lower values of α produce higher percentages of unphysical spin values, as can be inferred from equations (3) and (4). Therefore, our choice of α produces a minimum bias on the resulting spin distributions (a high concentration at $\hat{a} \approx 1$ would spuriously hide information on the high tail of the BH spin distribution).

One of the main uncertainties in our spin model lies on the initial value of the BH spin when considering their possible stellar origin, for which we test two possibilities: (i) a constant initial value (from $\hat{a}_{\rm initial} = 10^{-4}$ to 0.5[1]) and (ii) an initial value proportional to the BH mass. As we will show in Section 3, the choice of the initial spin value does not affect our results significantly. Moreover, the general conclusions of this work are preserved even for the case of spinless initial BHs. The most sensitive population to the inclusion of an initial BH spin is low-mass BHs (i.e. $M_{\rm BH} < 10^6\,{\rm M}_\odot$) since most of them have very few accretion episodes and practically no merger events during their entire lifetimes; as a note of caution, we remind the reader that a null initial spin is not likely to occur in a BH with a stellar origin.

In the case when a BH is assigned an initial spin (apart from a merger event), the spin direction will depend on the process that triggers the BH birth. Thus, the direction is given by (i) the angular momentum of the galaxy disc (similar to equation 5), in the case of disc instabilities, and (ii) the angular momentum of the galaxy disc weighted by the gas mass of each merging galaxy (similar to equation 7), in the case of galaxy mergers. The final value of the spin will be only a function of the accretion and assembly history of the BH.

This model provides a complete characterization of a supermassive BH, giving information on both its mass and spin. These

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[1] These initial spin values are consistent with results from hydrodynamic simulations (see Shapiro 2005 and references therein).

quantities strongly depend on the mass of cold gas accreted on to the BH. The great advantage of our model is that accretion discs are consistently given by our semi-analytic model within a universe where structures grow hierarchically, instead of being obtained from the assumption of specific distributions of Eddington accretion ratios as in other works (e.g. Sikora et al. 2007). Indeed, the redshift evolution of the accretion rate density on to a BH found by LCP08 (see their fig. 2) is consistent with the empirical estimations given by Merloni & Heinz (2008). Moreover, the evolution of the QSO luminosity function obtained from SAG is in good agreement with observational results (Wolf et al. 2003; Croom et al. 2004). Consequently, the resulting distributions of accretion disc masses and Eddington rates are consistent with what was adopted in previous Monte Carlo models.

2.4 Accretion disc orientation: inferred or random?

An important improvement presented by this model resides in the use of the known, vectorial angular momenta of the components of model galaxies to infer the direction of the angular momentum of the accretion disc. This depends on the physical process that triggers the accretion event, i.e. gas cooling, disc instabilities or galaxy mergers, as detailed above. Here, we describe the main advantages of this approach.

Fig. 1 shows the distributions of bulge masses for galaxies hosting central BHs with low and high spin values at $z = 0$ (dashed and solid lines, respectively), for a model where the angular momentum of the accretion disc depends on the process responsible for the gas accretion on to the central BH (equations 5 and 7) (Model A, black lines), and a model that uses randomly oriented accretion discs (Model B, grey lines). Both models take the K05 alignment criterion into account and use a constant initial BH spin $\hat{a}_{\rm initial} = 0.01$. As can be seen, in Model A, the fraction of galaxies with bulges of masses $M_{\rm Bulge} \gtrsim 3 \times 10^9\,{\rm M}_\odot$ hosting low-spin BHs decreases faster than in Model B, while both models show similar fractions of galaxies for a given bulge mass that host BHs with high spin values. Results from both models indicate that massive bulges host exclusively high-spin BHs. Taking into account that the most massive galaxies are ellipticals (Conselice 2006), we find that Model A, which shows a slightly clearer connection between massive galaxies and high BH spin values, supports the conjecture proposed by Sikora et al. (2007) that the radio loudness bimodality can be explained by the morphology-related bimodality of the BH spin distribution. Sections 3 and 4 are devoted to explore the predictions of this model.

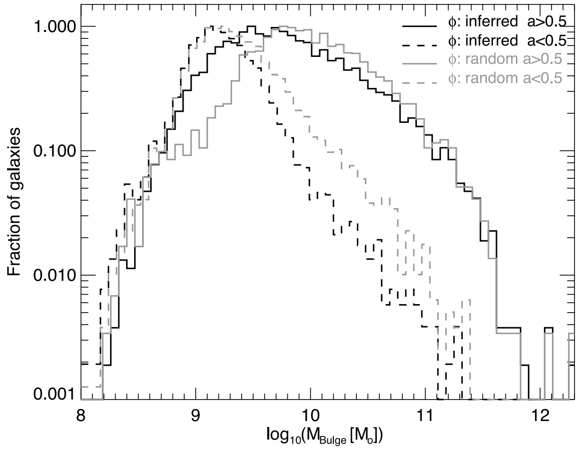

Figure 1. Distributions of $z = 0$ bulge masses for different ranges of final BH spin values, $\hat{a} < 0.5$ (dashed lines) and $\hat{a} \geq 0.5$ (solid lines). Black lines correspond to a model where accretion disc orientations are inferred from galaxy discs according to the process that triggers the accretion event; grey lines denote random accretion disc orientations. Both models take the K05 alignment criterion into account and use a constant initial BH spin value $\hat{a}_{\rm initial} = 0.01$.

3 CONNECTION BETWEEN BLACK HOLE SPIN DISTRIBUTIONS AND HOST GALAXY PROPERTIES

The main purpose of this work is to find a link between the properties of BHs and those of their host galaxies. In order to test the reliability of the possible relations obtained, we evaluate their dependence on different physical assumptions included in our BH spin model, such as the initial value of the BH spin and the alignment of the accretion disc.

Fig. 2 shows average growth tracks for BHs hosted by elliptical (top panel) and spiral galaxies (bottom panel). In both cases, we show BHs with masses $M_{\rm BH} > 10^6\,{\rm M}_\odot$, separated in three mass bins, each containing the same number of BHs. The morphological criterion to distinguish between elliptical and spirals considers the fraction $M_{\rm Bulge}/M_{\rm StellarTotal}$ between the bulge mass and the total stellar mass of the galaxy. We consider as ellipticals galaxies those with $r = M_{\rm Bulge}/M_{\rm StellarTotal} > r_{\rm thresh} = 0.95$, chosen in order to recover observed morphological distributions (see LCP08). These tracks indicate that, at all times, ellipticals host more massive BHs than spirals. Besides, the latter tends to stop the growth of their central BH at earlier times. These results do not depend on the details of the BH spin model. The differences in final mass and assembly history of the BHs can produce different final BH spins, a possibility that we now turn to.

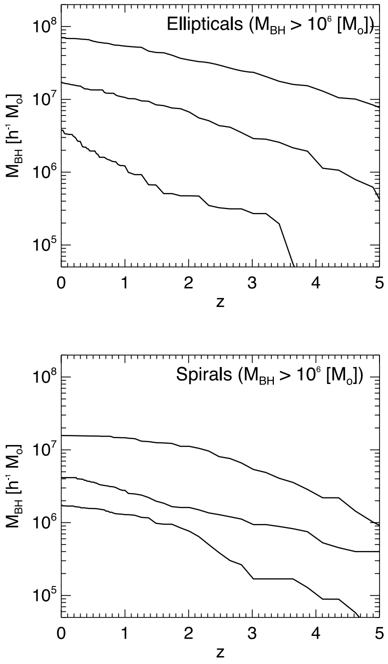

Figure 2. History of average BH growth for elliptical and spiral galaxies (top and bottom panels, respectively). Different lines show different average final BH masses (each mass bin contains equal number of BHs). Elliptical galaxies are selected according to $M_{\rm Bulge}/M_{\rm StellarTotal} > 0.95$, while spirals satisfy the condition $0 < M_{\rm Bulge}/M_{\rm StellarTotal} < 0.95$.

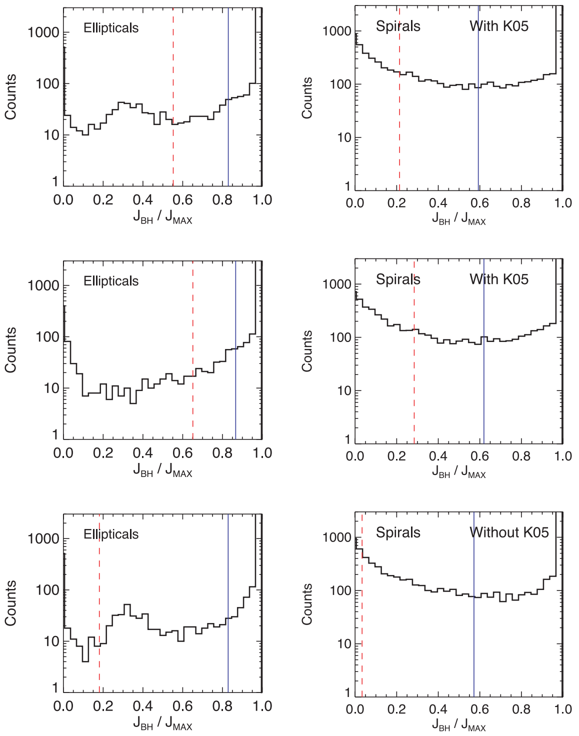

Figure 3. Distributions of BH spins at $z = 0$ hosted by elliptical (left-hand panels) and spiral galaxies (right-hand panels) from Model A, in which the direction of the accretion disc angular momentum is inferred from the process responsible for the gas accretion on to the central BH. The distributions are obtained from a constant initial BH spin $\hat{a}_{\rm initial} = 0.01$ and the K05 alignment criterion (upper panels) from $\hat{a}_{\rm initial} = M_{\rm BH,initial}/10^7\,{\rm M}_\odot$ and K05 (middle panels) and from $\hat{a}_{\rm initial} = 0.01$ and by adding the angular momentum of the accretion disc to the BH spin without considering the K05 criterion (lower panels). The vertical solid lines represent the average values of BH spin obtained from the histograms. For reference, the average values of BH spin obtained from randomly oriented accretion discs (Model B) are shown as vertical dashed lines.

Fig. 3 shows the BH spin distribution for BHs hosted by elliptical (left-hand panels) and spiral (right-hand panels) galaxies for three different versions of Model A: (i) using a constant initial BH spin $\hat{a}_{\rm initial} = 0.01$ and the K05 alignment criterion (upper panels), (ii) also with K05 and considering an initial BH spin proportional to the BH mass, $\hat{a}_{\rm initial} = M_{\rm BH,initial}/10^7\,{\rm M}_\odot$ (middle panels), and (iii) adopting the same initial BH spin as in (i) but without considering K05 (lower panels). Vertical solid lines represent the average BH spin using the full sample for each morphological type. For reference, average values from Model B are shown by the dashed lines.

In all cases considered, elliptical galaxies host both rapidly and slowly rotating BHs (the distributions show two peaks, at $\hat{a} \sim 0$ and 1), with a marked preference for high rotation; low values of spin are associated with low-stellar-mass galaxies ($M_{\rm Stellar} \lesssim 10^{10}\,{\rm M}_\odot$), with BH growth histories characterized by a typically low number of accretion episodes. Spiral galaxies, on the other hand, show a larger population of low-spin BHs. Even though spirals also show a peak at $\hat{a} \sim 1$, the average values of BH spin in ellipticals, for both Models A and B, are always higher than the average BH spin in spirals. This trend does not depend on the morphology criterion, since threshold values $r_{\rm thresh} \gtrsim 0.7$ practically produce the same spin distributions (i.e. variations in the average values are smaller than 20 per cent). Moreover, even a threshold as small as $r_{\rm thresh} = 0.5$ produces the same trend of increasing spin values for BHs hosted by elliptical galaxies. Our results change only slightly when the model does not consider the K05 criterion (lower panels), producing an almost negligible decrease of the average BH spin for both elliptical and spiral galaxies. However, the effect of not applying the criterion K05 has strong impact on Model B, producing very low spin values in all populations (i.e. accretion episodes randomly add/subtract angular momentum to the BH).

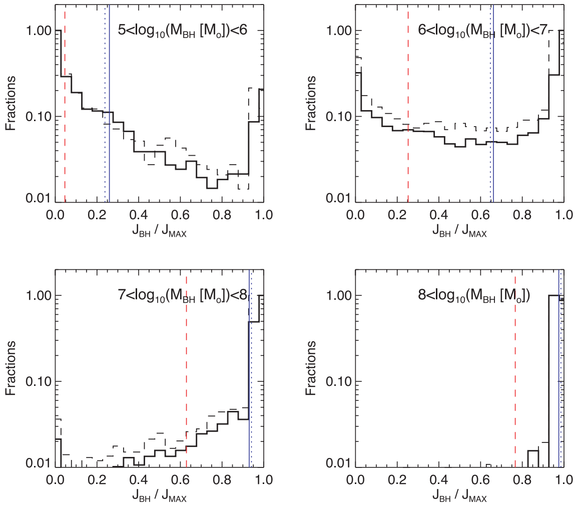

Figure 4. Normalized distributions of BH spin in four different BH mass bins obtained from Model A using a constant initial BH spin $\hat{a}_{\rm initial} = 0.01$ and the K05 alignment criterion. Solid vertical lines indicate average values of the BH spin calculated from the distributions shown in each panel. For reference, we also show the average values obtained from Model A without K05 (dotted lines) and Model B with K05 (dashed lines). The dashed histogram shows the distributions of Model A with K05 and initially spinless BHs.

This morphology-related dichotomy also arises from the analysis of BH spin distributions as a function of the BH mass. Fig. 4 shows the resulting normalized distributions from Model A with an initial BH spin $\hat{a}_{\rm initial} = 0.01$ and K05 alignments for four different BH mass ranges. The distributions are characterized by a progressive increase of the relative number of BHs with high spin values as we move to higher BH masses. This is clearly shown by the average values of BH spins represented by the vertical solid lines. Taking into account that our model reproduces the well-known BH–bulge mass relation (e.g. Magorrian et al. 1998; Gebhardt et al. 2000; Häring & Rix 2004), the link between massive elliptical galaxies and high BH spins is also recovered (see Fig. 3). The similar average values denoted by solid (Model A with K05) and dotted (Model A without K05) lines support our previous conclusion about the minor influence of the K05 alignment criterion on the BH spins. Although the average values from Model B (random angles with K05; dashed lines) are different from those given by Model A, the general behaviours of the average values are similar in both models. This is opposite to previous results by King, Pringle & Hofmann 2008, where the most massive objects with BH spins obtained by considering random angles show the inverse trend. The distributions for Model A with K05 and with a null initial BH spin are shown as dashed histograms and, as can be seen, there are little differences with respect to the non-zero spin case (solid histogram), and the increase in the average spin value as a function of BH mass is also obtained.

The three different scenarios explored here imply that massive ellipticals host more rapidly rotating BHs than spirals, as Sikora et al. (2007) proposed in their revised version of the 'spin paradigm'. This fact, together with the lack of a dependence of the $z = 0$ BH spin distributions on their initial value, confirms that the accretion and assembly history almost entirely define the final BH spin value. This was suggested earlier by our analysis of the BH growth tracks (Fig. 2). This result is contrary to what is found from randomly oriented accretion discs, since in this case the final distribution retains the memory of its initial conditions, as has already been reported in previous works (e.g. Volonteri et al. 2005). We also note that the K05 criterion has a small impact on the final average value of the BH spin. In the following section, we discuss into more detail the effects of considering K05 by using an individual example galaxy extracted from the model.

4 BLACK HOLE SPIN DEVELOPMENT

In this section, we present in detail the assessment of the contribution from each BH growth mechanism to the final spin value. We also evaluate the influence of assumptions regarding the accretion disc orientation and the effect of K05 alignments.

Fig. 5 shows the contribution of each BH growth mechanism to the BH spin value at $z = 0$ including mergers between BHs, and gas accretion driven by gas cooling processes, galaxy minor/major mergers and disc instabilities in the host galaxy. The calculation of the contributions from each mechanism is explained in detail in Section 2.3. The left-hand panel shows the results obtained from Model B with a constant initial BH spin $\hat{a}_{\mathrm{initial}} = 0.01$ and the K05 alignment criterion. We can see that the main spin-up mechanisms are disc instabilities and galaxy major mergers, the same processes that provide the main source of BH growth (fig. 2 in LCP08). This result is not necessarily expected a priori since, in Model B, the gas involved in minor and major mergers comes from different galaxies with random galaxy disc orientations, which may originate a misalignment of the accretion disc. Note that gas cooling processes produce a minor average contribution throughout the whole BH spin range, mainly due to the low-mass accretion rates during this process in addition to the random relative orientations, which result in roughly alternating additions and subtractions to the BH spin modulus.

The other two plots of Fig. 5 show results from Model A, with and without considering K05 alignments (middle and right-hand panels, respectively). In both cases, we set a constant initial BH spin $\hat{a}_{\mathrm{initial}} = 0.01$. We can see that, as in Model B (left-hand panel), disc instabilities are also one of the main spin-up mechanisms. However, the main difference with respect to the case of randomly oriented accretion discs is the important influence gained by gas cooling processes. The contribution of minor mergers also becomes more important than in Model B, being comparable to that of major mergers.

These results can be understood recalling that, during galaxy mergers, the angular momentum of the accretion disc arises as a result of the contribution from the gas mass-weighted angular momenta of the merging galaxies, while in self-interaction processes, like gas cooling and disc instabilities, the accretion disc simply takes the direction of the host halo angular momentum or the galaxy disc, respectively. This indicates that, at high redshifts, the first non-aligned accretion discs are likely to come from galaxy mergers. Taking into account the comparable influence of disc instabilities and gas cooling processes on the results of Model A, our conclusions on the development of the BH spin based on this model would not be strongly affected by the current modelling of disc instabilities, which is a simplified version of the actual process taking place in real galaxies (Athanassoula 2008). This is not necessarily true for Model B, where disc instabilities are major contributors to the BH spin.

Finally, mergers between BHs make a low relative contributions to the final value of the BH spin in all the three cases analysed. This is in agreement with previous works that indicate that high spins are achieved by accretion of baryonic matter rather than by mergers between BHs (e.g. Moderski & Sikora 1996; Moderski, Sikora & Lasota 1998; Hughes & Blanford 2003; Berti & Volonteri 2008; Peirani & de Freitas 2008). We remark that the relative importance of each growth mechanism is not affected by changes in the initial BH spin values tested in this work.

These results are only slightly modified when K05 alignments are not used, in which case the angular momentum of the disc is simply vectorially added to the BH spin without considering alignments (right-hand panel of Fig. 5). In this case, gas cooling processes and disc instabilities contribute to the BH spin in a rather similar way to the case where the K05 criterion is considered. This indicates that the angular momentum of accretion discs is mainly distributed within narrow cones around the BH spin direction, implying a slightly increased final spin value for a model with K05. In the more rare case of counter-alignments, the accretion episodes can also produce more important spin-down effects.

Regarding the effect of K05 alignments, we focus on an individual case in order to illustrate its effect on the BH spin development. Fig. 6 shows the evolution of several properties of the BH–disc

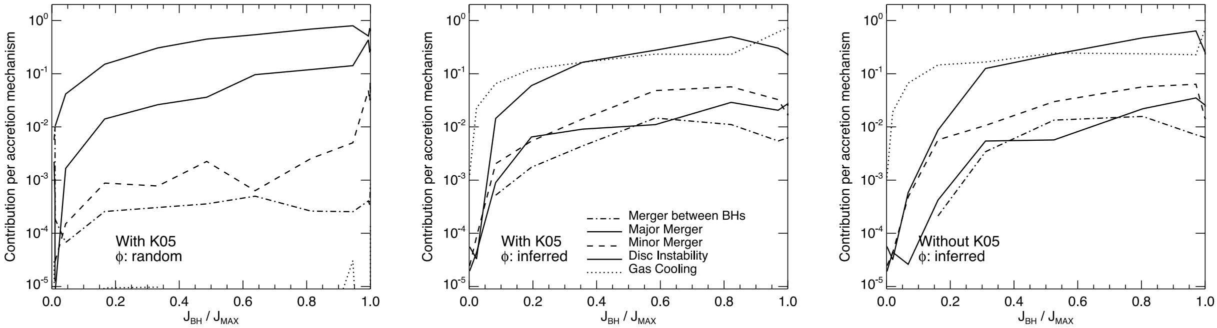

Figure 5. Contribution to the final BH spin from the five different mechanisms involved in the BH growth: mergers between BHs (dot–dashed line), and gas accretion driven by galaxy major mergers (triple dot–dashed lines), galaxy minor mergers (dashed line), galaxy disc instabilities (solid line) and gas cooling (dotted lines). Left-hand panel: results from Model B with a constant initial BH spin $\hat{a}_{\mathrm{initial}} = 0.01$ and the K05 alignment criterion. Middle panel: results from Model A, with $\hat{a}_{\mathrm{initial}} = 0.01$ and K05. Right-hand panel: same as middle panel but without the K05 criterion.

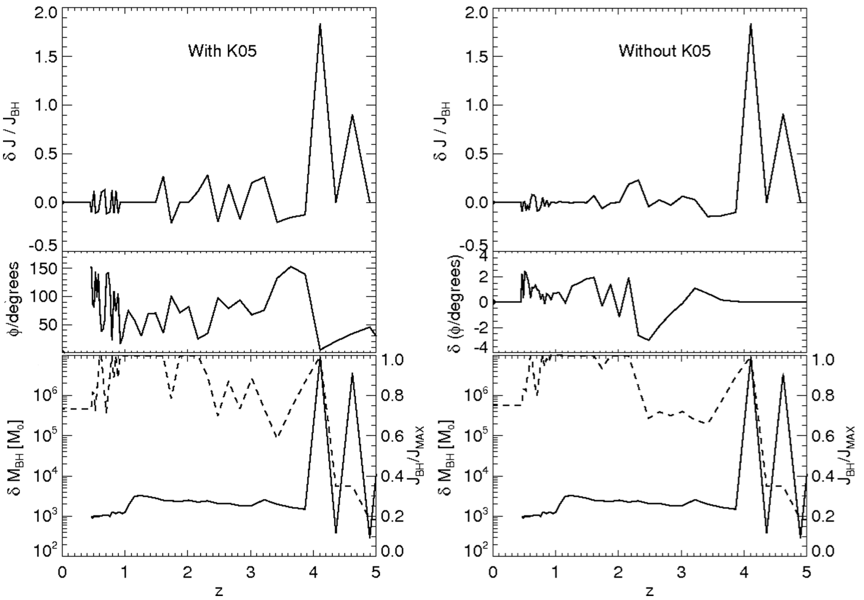

Figure 6. Redshift evolution of properties of the BH–disc system for an example galaxy extracted from SAG (spiral galaxy with $z = 0$ stellar mass $M_{\rm Stellar} = 8 \times 10^9\,{\rm M}_{\odot}$ and a BH mass of $M_{\rm BH} = 2 \times 10^7\,{\rm M}_{\odot}$). The left- and right-hand panels show the results from Model A with and without the K05 alignment criterion, respectively. The upper panels show the relative contribution of the angular momentum of the accretion discs to the angular momentum of the BH before the accretion, $J_{\rm BH} \equiv J_{\rm BH}^{\rm initial}$, giving a variation $\delta J = J_{\rm BH}^{\rm final} - J_{\rm BH}$ between consecutive snapshots of the N-body simulation. The middle-left panel presents the angle between the accretion disc and the BH spin, ϕ; the middle-right panel shows the variation in ϕ when the K05 criterion is removed. Lower panels show the mass accreted by the BH and the BH spin development in solid and dashed lines, respectively.

system of one example galaxy taken from Model A, with and without considering the K05 alignment criterion (left- and right-hand panels, respectively). The upper panels show the relative contribution to the angular momentum of the BH, $\delta J/J_{\rm BH}$ (where $\delta J = J_{\rm BH}^{\rm final} - J_{\rm BH}^{\rm initial}$ is the angular momentum variation between consecutive snapshots of the underlying N-body simulation and $J_{\rm BH} = J_{\rm BH}^{\rm initial}$), coming from accretion discs formed by the different gas accretion events (see Fig. 5). In both cases, with and without K05, some accretion episodes contribute to the BH angular momentum in amounts comparable or even higher than the current value of $J_{\rm BH}$. The middle-left panel shows the angle between the angular momentum of the accretion disc and the BH spin; the middle-right panel presents the variation in this angle arising from not including the K05 criterion. Lower panels depict the mass accreted by the BH in each snapshot (left-hand y-axis) and the BH spin history (right-hand y-axis). Note that the inclusion of K05 induces important changes in the details of the BH spin development. In particular, the accretion episodes that take place between $2.5 \leq z \leq 3.5$ do not significantly change the BH spin value when K05 is not applied, whereas when considering K05 the BH spin shows important variations. However, there is no final important net difference between these two models, since the sequence of accretion episodes that increase/decrease the BH spin almost cancel each other completely. Note that applying K05 also has a small effect on the resulting angles between BH spins and the galaxy angular momenta, producing differences of less than 4°. Finally, it is interesting to note, by looking at the middle panels, that in ~60 per cent of the accretion episodes the angle between the angular momenta of the disc and the BH is $\phi < 90°$.

Our inclusion of accretion disc orientations arising from the LSS, with or without K05 alignments, produces important changes in the contributions of different processes to the BH spin development, with respect to the results obtained using random orientations. This could have an important impact in our understanding of the connection between the BH spin and the luminous activity of AGN. For instance, recent studies by Ciotti & Ostriker (2007) show that RL QSOs might be produced by recycled gas rather than by mergers. In our model, these objects would be characterized by high spin values (see for instance Fig. 5); however, if we considered a Monte Carlo model, these objects would probably show a low spin (e.g. King & Pringle 2007), leading to a completely different interpretation of the physical phenomenon at work.

5 BEHIND THE NATURE OF ACTIVE GALACTIC NUCLEI RADIO LOUDNESS

The results of our model have shown that the properties of BHs and their host galaxies are closely connected, in agreement with numerous observational and theoretical works on this subject. However, our model does not provide direct information on the radio loudness of the galaxy population. In an attempt to classify a galaxy as a RL object, we explore different possibilities using available properties of galaxies and their BHs provided by the model. Among the most important quantities required to fully characterize the BH and its accretion disc are the way in which gas accretion proceeds (extensively discussed in Section 1), the BH mass, the BH spin and the magnetic field.

Observational results indicate that the average BH mass in RL systems is about twice as large as in RQ galaxies (e.g. Corbin 1997; Laor 2000; Lacy et al. 2001; Boroson 2002; Jarvis & McLure 2002; Metcalf & Magliocchetti 2006). Taking into account the well-known relationship between BH and host bulge mass, it is natural to extend the dependence of radio loudness to the stellar mass of the host galaxy. None the less, both populations of RL and RQ QSOs have been detected in massive elliptical galaxies (e.g. Floyd et al. 2004); also, BHs of equal mass show differing radio luminosities by up to ~4 orders of magnitude (Ho 2002; Dunlop et al. 2003; Sikora et al. 2007). Therefore, it can be inferred that the influence of this BH property on the jet production, and the consequent strength of the radio emission, is secondary. Other results in this direction are found by Merloni et al. (2003).

The second parameter that may play a role in the RL/RQ dichotomy is the amplitude of the local magnetic field from accretion flows which, in some cases, can produce large-scale fields that would help collimate strong relativistic jets (Krolik & Hawley 2007). It has been argued, however, that the presence of such fields may not be of primary importance (Spruit 2008). In microquasars, that share the same physical principles than AGN on much smaller scales, it is possible that cold winds are responsible for the collimation of jets (Bosch-Ramon, Romero & Paredes 2006). This alternative further diminishes the potential relevance of magnetic fields as a primary collimation mechanism.

The third physical property that can be linked to the radio loudness phenomenon is the BH spin as has been suggested by several authors (e.g. Wilson & Colbert 1995; Lacy et al. 2001; Lacy 2002; Hawley & Krolik 2006; Ballantyne 2007; Nemmen et al. 2007; Sikora et al. 2007; Volonteri et al. 2007). Furthermore, a recent study by Lindner & Fragile (2007) shows that the jet direction is influenced by the BH spin. Therefore, in addition to the accretion rate, we consider the BH spin as another possible candidate to break the degeneracy between the RQ and RL populations.

With these caveats in mind, we assume that radio loudness is defined by the BH spin, the gas accretion rate ('accretion paradigm'), or combinations of both parameters (as in the 'revised spin paradigm', Sikora et al. 2007). We evaluate the possibility that radio loudness is defined by these criteria using observational results on the fraction of RL galaxies ($f_{\rm RL}$) which is thought to increase with both BH and stellar mass (Corbin 1997; Laor 2000; Lacy et al. 2001; Boroson 2002; Jarvis & McLure 2002; Best et al. 2005; Metcalf & Magliocchetti 2006). These relations are still a matter of debate, since it has been argued that they can simply be the result of observational biases (see for instance White et al. 2007). In addition, since there are no measurements of $f_{\rm RL}$ using complete samples of galaxies to date, we are limited to make qualitative comparisons to the observed data. The most complete study performed to date was presented by Best et al. (2005) based on the Sloan Digital Sky Survey but, even in this case, they only consider FR I radio sources, characterized by low radio luminosities. We will attempt to distinguish between the predictions of Models A and B by using only qualitative comparisons.

To this aim, we focus on $z \approx 0$ active galaxies (i.e. with Eddington ratios $\lambda \equiv L_{\rm BH}/L_{\rm Edd} > 0$), and separate them into samples of model RL (MRL) galaxies selected using different upper limits in accretion rates, $\lambda < \lambda_{\rm MAX}$, with $\lambda_{\rm MAX} = 10^{-1}$, 10^{-2}, 10^{-3} and 10^{-4}, and three normalized minimum BH spin values, $\hat{a}_{\rm MIN} = 0.3, 0.6$ and 0.9. We test whether these MRL samples are able to mimic the observed RL population. Fig. 7 shows the resulting fractions of MRL galaxies, $f_{\rm MRL}$, as a function of stellar mass for Models A and B (cf. Section 2.4) using an initial BH spin $\hat{a}_{\rm initial} = 0.01$ and including K05 alignments. Fractions obtained using thresholds in the Eddington ratio only, $\lambda < \lambda_{\rm MAX}$, are represented by blue lines. Black lines show the results for galaxies selected using $\hat{a} > \hat{a}_{\rm MIN}$, and red lines show the results for samples obtained from the combination of limits on both spins and accretion rates. For reference, the results for the full population of active galaxies are represented by a black dashed line.

As can be seen, for Model A, the limits on Eddington ratios produce very similar fractions to what is obtained for the full AGN sample, mostly due to the lack of BHs with high λ values at low redshift. The main features for samples limited by λ are an increasing $f_{\rm MRL}$ with stellar mass for $M_{\rm Stellar} \lesssim 10^9\,{\rm M}_{\odot}$, with a plateau up to $M_{\rm Stellar} \approx 10^{10}\,{\rm M}_{\odot}$. Stringent limits, $\lambda_{\rm MAX} \lesssim 10^{-3}$, produce a decreasing $f_{\rm MRL}$ at the high-stellar-mass end. However, these limits are very restrictive since observed RL galaxies can show Eddington ratios as large as $\lambda \approx 10^{-2}$ (e.g. Ho 2002; Sikora et al. 2007). This aspect should be taken into account in order to test these particular predictions. These trends are at odds with the monotonically increasing observational relation mentioned above. There is little effect on these trends when considering the case of a null initial BH spin.

On the other hand, when considering thresholds on the BH spin alone, the fractions of MRL galaxies always increase with stellar mass. The results for the combined conditions, $\hat{a} > \hat{a}_{\rm MIN}$ and $\lambda < \lambda_{\rm MAX}$, are only shown for $\lambda_{\rm MAX} = 10^{-1}$ and 10^{-2}. These cases also show increasing relations between $f_{\rm MRL}$ and stellar mass because of the strong influence of the limits on the BH spin. Finally, for all the selection criteria analysed, Model B (right-hand panel of Fig. 7), characterized by random orientations, fails to produce monotonically increasing fractions of MRL galaxies as a function of stellar mass. When we consider null initial BH spins, the only appreciable change in the fractions of MRL galaxies is a slight increase in the slope of the relation with respect to the results shown in Fig. 7.

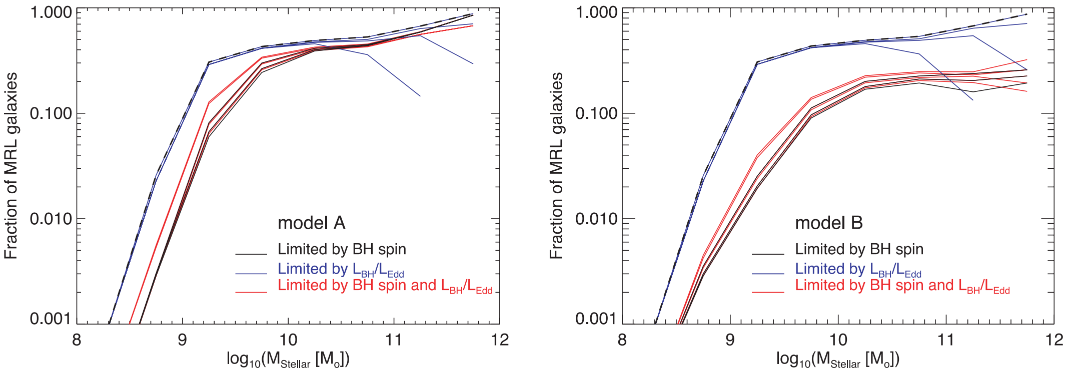

Figure 7. Fraction of $z < 0.1$ MRL galaxies as a function of stellar mass for Models A (left-hand panel) and B (right-hand panel), both using an initial BH spin $\hat{a}_{\rm initial} = 0.01$ and including K05 alignments. Blue lines show the fractions for samples with Eddington ratios $\lambda < \lambda_{\rm MAX}$, with $\lambda_{\rm MAX} = 10^{-1}$, 10^{-2}, 10^{-3} and 10^{-4} (top to bottom lines); black lines, the fractions for samples with BH spin $\hat{a} > \hat{a}_{\rm MIN}$, with $\hat{a}_{\rm MIN} = 0.3$, 0.6 and 0.9 (top to bottom lines); red lines show the fractions resulting from combinations of limits on both accretion rate and BH spin. For reference, we show the fraction of active galaxies as a function of stellar mass (black dashed lines).

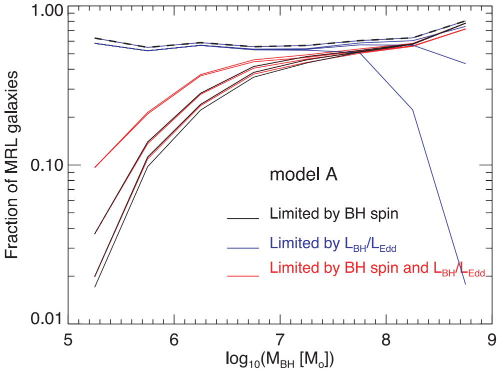

Figure 8. Fraction of MRL galaxies as a function of BH mass for Model A using an initial BH spin $\hat{a}_{\rm initial} = 0.01$ and including K05 alignments. Line types and galaxy samples are as in Fig. 7.

Fig. 8 shows the fractions of MRL galaxies as a function of BH mass for Model A (line colours are as in Fig. 7). As can be seen, the fractions of galaxies selected according to the three sets of criteria on BH spin and accretion rates show similar behaviours to those obtained as a function of stellar mass. The same similarity between the dependencies with BH and stellar mass arise for Model B, with milder or negligible trends of the MRL fractions with BH mass.

All the previous results correspond to the local Universe. From our results on the development of BH spin (see for instance Fig. 6), it is natural to expect smaller fractions $f_{\rm MRL}$ at higher redshifts, particularly when using the BH spin as the main parameter to define radio loudness. However, the fractions of active galaxies increase importantly at higher redshifts producing a combined effect. Galaxies hosting BHs with masses $M_{\rm BH} \gtrsim 10^8\,{\rm M}_{\odot}$ lead to higher fractions $f_{\rm MRL}$ with respect to those with BHs of the same mass in the local Universe, while galaxies with BHs masses in the range $M_{\rm BH} \lesssim 10^8\,{\rm M}_{\odot}$ show the expected decreased fractions. As the redshift increases the relation becomes steeper as a function of both BH and stellar mass. This prediction can be confirmed by further observations of high-redshift radio sources.

We have combined two models for the orientation of accretion discs with three sets of criteria related to the accretion and spin paradigms, with the aim of isolating the main parameters that characterize the radio loudness of galaxies. Our results indicate that the dependence of the fractions of MRL galaxies with BH and stellar mass is a qualitative match to the increasing trend showed by observational results when thresholds on the BH spin are applied. It is important to note that this is more naturally achieved in a model with LSS-oriented accretion discs. The most important aspect to emphasize from our results is that this qualitative agreement preferentially favours the 'spin paradigm' as the likely scenario for radio loudness in the Universe. We remind the reader that the observed trend is still in debate. Therefore, further observational data on AGN are required in order to reach a proper understanding of the biases involved in the measurements of fractions of RL galaxies. Only once this problem is solved it will be possible to attempt to tip the scales in favour a single model (e.g. A or B).

6 SUMMARY AND PERSPECTIVES

We have implemented a simple calculation of the BH spin in the semi-analytic model of galaxy formation described by LCP08 to study relationships between the BH spin, the BH mass and the host galaxy properties. The main advantage of using a semi-analytic model relies in the ability to follow, for the first time, the development of the BH spin from the contribution of different BH growth mechanisms, all immersed within a ΛCDM cosmology. Such processes are gas cooling, disc instabilities, galaxy mergers and mergers between BHs. Additionally, the model allows us to relate phenomena taking place at very small scales (BH and accretion disc) to those at larger scales (galaxy discs); we infer the orientation of the accretion disc using that of the source of accreted material (referred to as Model A). Thus, the angular momentum of the host halo is used when the accretion is driven by gas cooling, while that of the galaxy disc is considered during disc instability events; in the case of mergers, gas mass-weighted averages of the angular momentum of intervening galaxies are adopted. We also consider random accretion disc orientations (Model B), as has been adopted in several previous works (e.g. King & Pringle 2007; Volonteri et al. 2007).

The main results and conclusions of this work are summarized as follows.

(i) Massive bulges, and therefore giant elliptical galaxies, host almost exclusively rapidly rotating BHs. Although this effect is more pronounced in Model A than in Model B, in both models elliptical galaxies host, on average, BHs with higher spin values than spiral galaxies, in accordance with the revised 'spin paradigm' proposed by Sikora et al. (2007). Therefore, the morphology-related bimodality of radio loudness could be explained by the BH spin.

(ii) High-mass BHs ($M_{\rm BH} > 10^7\,{\rm M}_{\odot}$) in Model A show little dependence on the initial BH spin assigned to them, indicating that their spin is almost entirely determined by the accretion history. Additionally, including the K05 alignments of accretion discs only produces very mild changes in the final BH spin distribution. Results from Model B are found to be more dependent on the initial values of the BH spin and strongly dependent on whether the K05 alignment is applied or not.

(iii) For Model A, gas cooling processes and disc instabilities are the main contributors to the final BH spin. It is important to bear in mind that gas cooling processes produce very low relative accretion on to the BH. On the other hand, in Model B, the main mechanisms for BH spin-up are also those responsible for the highest accretion rates, namely galaxy mergers and disc instabilities. This represents the main difference between the two schemes adopted for the orientation of accretion discs.

(iv) We use measurements of the dependence of the fraction of RL galaxies as a function of stellar and BH masses in order to test different parameter combinations to select a population of model galaxies representative of the observed RL galaxy population. These parameters are assumed to be the accretion rate and/or the BH spin. We test three different criteria, using (i) an upper limit on the Eddington ratio ('accretion paradigm'), (ii) a lower limit on the BH spin and (iii) simultaneous limits on both quantities (similar to the revised version of the 'spin paradigm'). For Model A, we find that criterion (i) predicts a roughly constant fraction of possible RL galaxies as a function of BH and stellar mass (for $M_{\star} > 10^9\,{\rm M}_{\odot}$), while criterion (ii) produces a monotonically increasing relation. Finally, criterion (iii) also produces an increasing relation, although mostly due to the strong influence of the limit on the BH spin. For Model B, we find that none of the proposed criteria is able to produce an increasing fraction of RL galaxies with either the stellar or BH mass.

(v) Taking into account recent observational results (e.g. Best et al. 2005; Chiaberge, Capetti & Macchetto 2005; Metcalf & Magliocchetti 2006) reporting an increasing fraction of RL galaxies with BH and stellar masses, we find that the most suitable paradigm to explain radio loudness is the 'spin paradigm' (Sikora et al. 2007). Still, it should be taken into account that these measurements may be subject to observational biases (e.g. Cirasuolo et al. 2003; White et al. 2007).

The implementation of a BH spin model presented here can be used as a new tool to understand the role of different processes on both very large and very small scales, within an *ab initio* model of galaxy formation. Within our modelling we are able to reproduce results from Monte Carlo attempts at describing BHs and the RL galaxy population. Our analysis also singles out possible systematic biases in the model predictions resulting from the use of random orientations for the accretion discs which continuously form around BHs. Our finding of a possible influence of the LSS alignments on the detailed spin-up history of BHs can now also be considered in simple models, and be studied into more detail. However, new and improved observational constraints are still required to help distinguish between possible causes for the AGN radio activity in the Universe.

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