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Why are active galactic nuclei and host galaxies misaligned?

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ABSTRACT

It is well established observationally that the characteristic angular momentum axis on small scales around active galactic nuclei (AGN), traced by radio jets and the putative torus, is not well correlated with the large-scale angular momentum axis of the host galaxy. In this paper, we show that such misalignments arise naturally in high-resolution simulations in which we follow angular momentum transport and inflows from galaxy to sub-pc scales near AGN, triggered either during galaxy mergers or by instabilities in isolated discs. Sudden misalignments can sometimes be caused by single massive clumps falling into the centre slightly off-axis, but more generally, they arise even when the gas inflows are smooth and trace only global gravitational instabilities. When several nested, self-gravitating modes are present, the inner ones can precess and tumble in the potential of the outer modes. Resonant angular momentum exchange can flip or re-align the spin of an inner mode on a short time-scale, even without the presence of massive clumps. We therefore do not expect that AGN and their host galaxies will be preferentially aligned, nor should the relative alignment be an indicator of the AGN fuelling mechanism. We discuss implications of this conclusion for AGN feedback and black hole (BH) spin evolution. The misalignments may mean that even BHs accreting from smooth large-scale discs will not be spun up to maximal rotation and so have more modest radiative efficiencies and inefficient jet formation. Even more random orientations/lower spins are possible if there is further unresolved clumpiness in the gas, and more ordered accretion may occur if the inflow is slower and not self-gravitating.

Key words: galaxies: active – galaxies: evolution – quasars: general – cosmology: theory.

1 INTRODUCTION

Understanding accretion is critical for inferring the origin of the supermassive black hole (BH) population (Soltan 1982; Salucci et al. 1999; Shankar et al. 2004; Hopkins, Narayan & Hernquist 2006b). Most of the BH growth in the Universe is obscured by large columns of gas and dust, so knowing the behaviour of gas on scales $\sim$0.1–100 pc is a necessary ingredient in a full model of BH evolution (Antonucci 1982, 1993; Lawrence 1991; Risaliti, Maiolino & Salvati 1999; Simpson, Rawlings & Lacy 1999; Willott et al. 2000). The discovery of tight correlations between BH mass and host spheroid properties (e.g. mass, velocity dispersion, binding energy; Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Aller & Richstone 2007; Hopkins et al. 2007a,b; Feoli & Mancini 2009) implies that BH growth is coupled to galaxy formation. Models widely invoke some form of feedback from AGN to explain the origin of the BH–host relations, rapid quenching of star formation in bulges, the colour–magnitude relation and the cooling flow problem (e.g. Silk & Rees 1998; King 2003, 2005; Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005; Hopkins et al. 2008; Hopkins & Elvis 2010; Croton et al. 2006, and references therein).

However, despite these important links, the detailed processes in BH fuelling remain poorly understood. One critical long-standing puzzle is the consistent observational finding that there is little or no correlation between the angular momentum axis of material accreting on to the BH and the axis of the host galaxy. This has been observed with a number of different tracers, e.g. radio jets (expected to align with the axis of the BH spin or inner accretion disc, but see also Natarajan & Pringle 1998) or obscuring AGN 'torii' defining the plane along which material flows into the inner accretion disc (see e.g. Keel 1980; Lawrence & Elvis 1982; Ulvestad & Wilson 1984; Schmitt et al. 1997; Simcoe et al. 1997; Kinney et al. 2000;

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Gallimore et al. 2006; Zhang et al. 2009).[1] The nuclear disc is misaligned with the larger scale disc/galaxy inflows; but the latter must ultimately be the origin of the former, so this is not trivially expected.

This misalignment has a number of consequences. It constrains any model of AGN fuelling and has important implications for AGN obscuration. Not only does it constrain the origin of the 'torus', but misalignments between the inner and outer discs can potentially result in large covering factors of obscuration (even if the discs are thin; see e.g. Sanders et al. 1989; Fruscione et al. 2005; Nayakshin 2005; Hopkins et al. 2012a). It is critical for understanding the BH spin – if gas accreted from large scales in the galaxy conserves its axis of angular momentum as it falls on to the BH, then almost any high accretion rate event will spin the BH up to near-maximum ($a \approx 0.998$) and align it with the parent disc/inflow (e.g. Volonteri et al. 2005; Volonteri & Rees 2005; Berti & Volonteri 2008). However, if the angular momentum can be randomized on sufficiently small mass/time-scales ('chaotic accretion'), then not only will the lack of correlation with the host galaxy appear (King & Pringle 2007), but the typical spins are held low even in large accretion events (Moderski & Sikora 1996; King & Pringle 2006). Spin has important subsequent implications for BH–BH mergers and gravitational wave BH recoil (whether or not BHs will be expelled from the galaxy or rapidly damp any small recoil motion). And it is believed to be critical for the production of radio jets (at least in some scenarios; see Blandford & Znajek 1977; Begelman, Blandford & Rees 1984, but also compare Livio, Ogilvie & Pringle 1999). Jets and other AGN feedback sources are of critical importance for quenching cooling in massive galaxies, shaping the galaxy mass function, structuring galaxy clusters and resolving the 'cooling flow problem'.

Unfortunately, it is not generally possible to simultaneously model inflows from galactic scales and their behaviour on the small scales near the BHs that are relevant for this problem. Analytic models (Elitzur & Shlosman 2006; Nayakshin & King 2007; Kawakatu & Wada 2008) are limited by symmetry assumptions as well as the fact that these systems are highly non-linear, often chaotic and not in steady state (with inflow, outflow, star formation and feedback competing). Simulations of galaxies used to follow inflows are typically limited to a resolution of several 100 pc, much larger than the scales of interest (Cattaneo et al. 2005; Hopkins et al. 2005a,b). Other simulations which begin on small scales (taking some fixed initial conditions for the gas inside of $\lesssim$10 pc) cannot relate this to the larger scale material from which it must have originated (Wada & Norman 2002; Schartmann et al. 2009; Wada, Papadopoulos & Spaans 2009). Some exciting results have emerged from 'zoom-in' refinement techniques (see Colpi et al. 2007; Escala 2007; Mayer et al. 2007; Levine et al. 2008; Dotti et al. 2009), but computational expense has generally required restrictive assumptions (e.g. turning off cooling and star formation on small scales) or limited these to single example galaxies at a single instant in time (preventing statistical statements).

Recently, Hopkins & Quataert (2010a) attempted to build on these experiments to model the angular momentum transport required for massive BH growth and carried out a series of numerical simulations of inflow from galactic to BH scales. By 're-simulating' the central regions of galaxies in a series of stages, gas flows can be modelled over a range of galactic scales from ∼100 kpc to <0.1 pc. In Hopkins & Quataert (2010a), we show that quasar-level inflows (∼10 $M_{\odot}$ yr^{-1}) arise from global perturbations such as galaxy mergers and/or secular instabilities, which (when sufficiently strong) generate a cascade of subsequent instabilities (of varied morphology), and typically manifest near the radius of influence of the BH as a thick (torus-like), lopsided/eccentric gas plus stellar disc. In Hopkins & Quataert (2010b), we discuss evidence for the relics of such discs in nearby galaxies (Lauer et al. 1993, 1996; Bender et al. 2005). In Hopkins & Quataert (2011a), we discuss the detailed dynamics of these instabilities and how they drive large inflow rates, and in Hopkins et al. (2012a) their role in the obscuration of AGN.

In this paper, we show that the instabilities which drive inflows in these simulations naturally lead to large misalignments of the nuclear disc with respect to the disc of the host galaxy. We discuss the implications for the BH spin even in 'maximally conservative' scenarios where there is no unresolved sub-grid clumpiness in the interstellar medium (ISM) in our simulations (there almost certainly is such).

2 THE SIMULATIONS

The simulations used here are taken from a suite used to study the physics of gas inflow from galactic to small scales in Hopkins & Quataert (2010a,b, 2011a,b) and Hopkins (2010). The numerical properties of each simulation are specifically given in Hopkins & Quataert (2010a, tables 1–3), but we briefly describe them here. In order to probe the very large range in spatial and mass scales, we carry out a series of 're-simulations'. First, we simulate the dynamics on galaxy scales. Specifically, we use representative examples of gas-rich galaxy–galaxy merger simulations and isolated, moderately bar-unstable disc simulations. These are well resolved down to ∼100–500 pc. We use the conditions at these radii (at several times) as the initial conditions for intermediate-scale re-simulations of the sub-kpc dynamics. In these re-simulations, the smaller volume is simulated at higher resolution, allowing us to resolve the subsequent dynamics down to ∼10 pc scales – these re-simulations approximate the nearly instantaneous behaviour of the gas on sub-kpc scales in response to the conditions at ∼kpc set by galaxy-scale dynamics. We then repeat our re-simulation method to follow the dynamics down to sub-pc scales where the gas begins to form a standard accretion disc.

Our re-simulations are *not* intended to provide an exact realization of the small-scale dynamics of the larger scale simulation that motivated the initial conditions of each re-simulation (in the manner of particle splitting or adaptive mesh refinement techniques). Rather, our goal is to identify the dominant mechanism(s) of angular exchange and transport in galactic nuclei and which parameters they depend on. This approach clearly has limitations, especially at the outer boundaries of the simulations; however, it also has a major advantage. By not requiring the conditions at small radii to be uniquely set by a larger scale 'parent' simulation, we can run a series of simulations with otherwise identical conditions (on that scale) but systematically vary one parameter (e.g., gas fraction or the ISM model) over a large dynamic range. This allows us to identify the physics and galaxy properties that have the biggest effect on gas inflow in galactic nuclei. The diversity of behaviours seen in the simulations, and a desire to marginalize over the uncertain ISM physics, makes such a parameter survey critical.

[1] We stress that this is not necessarily the same as a lack of correlation between obscuration and host galaxy alignment, since significant obscuring columns can come from large scales in e.g. starbursts or edge-on discs (Hopkins et al. 2006a; Hopkins & Hernquist 2006; Rigby et al. 2006; Zakamska et al. 2006; Hayward et al. 2011; Lagos et al. 2011).

The simulations were performed with the TREESPH code GADGET-3 (Springel 2005); they include stellar discs, bulges, dark matter haloes, gas and BHs. For this study, we wish to isolate the physics of gas inflow and so do not include explicit models for BH feedback (see Section 4). The simulations include gas cooling and star formation, with gas forming stars at a rate $\dot{\rho}_* \propto \rho^{3/2}$ motivated by observations (Kennicutt 1998) and normalized so that a Milky Way-like galaxy has total $\dot{M}_* \approx 1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Varying the exact slope or normalization of this assumption has no qualitative effect on our conclusions. Because we cannot resolve the detailed processes of supernova explosions, stellar winds and radiative feedback, feedback from stars is modelled with an effective equation of state (Springel & Hernquist 2003). In this model, feedback is assumed to generate a non-thermal (turbulent, in reality) sound speed that depends on the local star formation rate, and thus the gas density; the results shown span a wide range in this 'effective sound speed' without any strong dependence on the exact value (detailed comparisons of the effects on morphology and inflow are shown in Hopkins & Quataert 2010a, comparisons of mode growth and torques in Hopkins & Quataert 2011a). A more detailed comparison with the explicit stellar feedback models presented in Hopkins, Quataert & Murray (2011, 2012b,c) will be the subject of future work.

We 'begin' with galaxy-scale simulations that motivate the initial conditions chosen for the smaller scale re-simulation calculations. These include galaxy–galaxy mergers and isolated bar-(un)stable discs. These simulations have 0.5×10^6 particles and 50 pc spatial resolution (details in Di Matteo et al. 2005; Cox et al. 2006; Robertson et al. 2006; Younger et al. 2008; Hopkins et al. 2009); a subset have $\sim 10^7$ particles and 20 pc resolution. From this suite, we select representative simulations of gas-rich major mergers of Milky Way mass galaxies and their isolated bar-unstable analogues to provide the basis for our re-simulations. Small variations in the orbits or the structural properties of the galaxies will change the details of the tidal and bar features on large scales; however, we show in Hopkins & Quataert (2010a) that the precise details of these large-scale simulations do not *instantaneously* alter the dynamics on small scales (see figs A2 and A3 therein). Rather, the local dynamics depends on global parameters such as the gas mass channelled into the central region, relative to the pre-existing bulge, disc and BH mass (set, of course, by the large-scale inflows, but once set, robust to variations in the details of that inflow structure).

Following gas down to the BH accretion disc requires much higher spatial resolution than that is achievable in the galaxy-scale simulations. We therefore select snapshots from the galaxy-scale simulations at key epochs and isolate the central 0.1–1 kpc region which contains most of the gas driven in from large scales (typical $\sim 10^{10}\,\mathrm{M}_\odot$ in gas, over scale-length $\sim$0.3–0.5 kpc). From this mass distribution, we then re-populate the gas in the central regions at much higher resolution and simulate the dynamics for several local dynamical times. These 'intermediate-scale' simulations involve 10^6 particles, with a resolution of a few pc and particle masses of $\approx 10^4\,\mathrm{M}_\odot$. We have run $\sim$50 such re-simulations, corresponding to variations in the global system properties, the models of star formation and feedback and the exact time in the larger scale dynamics at which the re-simulation occurs. Hopkins & Quataert (2010a) present tests of this re-simulation approach and show that it is reasonably robust for this problem. This is largely because, for gas-rich discy systems, the central $\sim$300 pc becomes strongly self-gravitating, generating instabilities that dominate the subsequent dynamics.

We repeat our re-simulation process once more, using the central $\sim$10–30 pc of the first re-simulations to initialize a new set of 'small-scale' simulations. These typically have $\sim 10^6$–10^7 particles, a spatial resolution of 0.1 pc and a particle mass $\approx 100\,\mathrm{M}_\odot$. We carried out $\sim$50 such simulations to test the robustness of our conclusions and survey the parameter space of galaxy properties. These final re-simulations are evolved for $\sim 10^7$ yr – many dynamical times at 0.1 pc, but very short relative to the dynamical times of the larger scale parent simulations.

To check that our re-simulation approach has not introduced any artificial behaviour, we have run a small number of higher resolution 'bridging' simulations. These result in slightly worse ultimate spatial resolution than the net effect of the 're-simulations', but they obviate the need for the re-simulation and bridge the scales of the above simulation suites. These include six simulations on galaxy scales (three mergers, three isolated discs) with $>10^7$ gas particles and 10 pc softening lengths. While not quite as high-resolution as our 'intermediate-scale' re-simulation runs, these provide an important check on the results of the latter and are run self-consistently for 4×10^9 yr. We have followed the same procedure on small scales: running five 'intermediate-scale' simulations (with a range of gas fraction and bulge-to-disc ratio) with $>10^7$ gas particles and softening of $\sim$0.3 pc; these extend from scales of $\sim$0.3–1000 pc and are run for 2×10^8 yr. In Hopkins & Quataert (2010a, 2011a), we explicitly compare the results of these simulations with those of our 're-simulations' in the dynamic range where they overlap and find that they are very similar (see e.g. the discussion and figs 9–13 and A4 in Hopkins & Quataert 2010a and fig. 8 in Hopkins & Quataert 2011a), supporting the methodology used for most of our calculations.

We note that recent studies comparing cosmological simulations done with GADGET and the new moving mesh code AREPO (Springel 2010) have called into question the reliability of smoothed particle hydrodynamics (SPH) for some problems related to galaxy formation in a cosmological context (Keres et al. 2011; Sijacki et al. 2011; Vogelsberger et al. 2011; Bauer & Springel 2012). However, we have also performed idealized simulations of mergers between individual galaxies and found excellent agreement between GADGET and AREPO for e.g. gas-inflow rates, star formation histories and the mass in the ensuing starbursts (Hayward et al., in preparation). Simulations of this type circumvent many of the issues with SPH by characterizing the gas on small scales with an effective equation of state (as in the present study), rather than attempting to resolve the various gas phases explicitly. The discrepancies above are also minimized when the flows of interest are supersonic (as opposed to subsonic), which is very much the case here (Kitsionas et al. 2009; Price & Federrath 2010; Bauer & Springel 2012). We have also performed direct resolution studies of simulations at each 'scale' (with up to 168 times as many particles) and find good convergence (see e.g. section A1 and fig. A1 in Hopkins & Quataert 2010a and fig. 4 in Hopkins & Quataert 2011a).

3 RESULTS

Fig. 1 shows the central tens of pc in several of our 'intermediate-scale' bridging simulations, in which inflows are followed from $\sim$1–1000 pc scales. Of course, resolving those larger scales and the resulting inflow means that the resolution on these scales is not quite as good as our 'small-scale' runs, but the $\sim$10 pc scale disc is marginally resolved (in length/mass; the vertical/internal structure is not resolved below these sizes in these runs).[2] There are clear cases

[2] See fig. 10 in Hopkins & Quataert (2010a), which shows the vertical scale heights as a function of radius in these and the others of our simulation suites

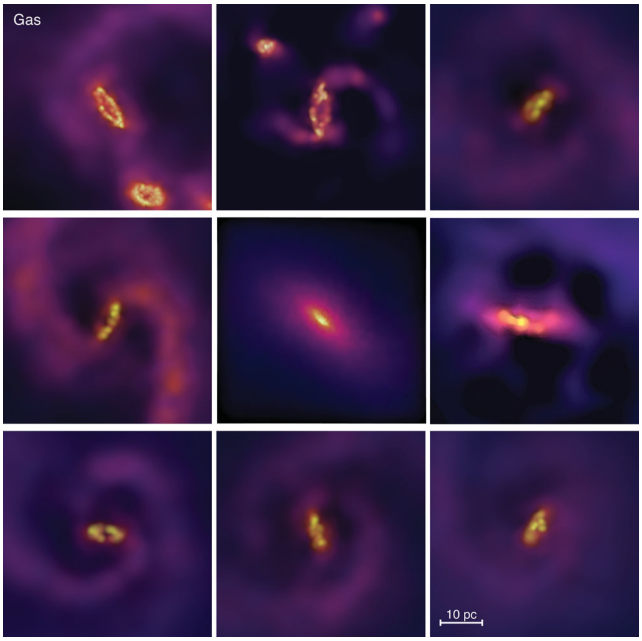

Figure 1. Illustration of twists, warps and misalignments in some of our simulations (each panel is a different simulation). Projected gas density (intensity) and specific star formation rate (colour, increasing from blue through yellow) are shown. Times are chosen randomly near the peak of the BH accretion. All are projected 'face on' to the disc on large scales (angular momentum averaged over the entire box). These are ultra-high-resolution 'intermediate-scale' simulations which can resolve twists and misalignments between the 'torus' and larger scale disc. There is frequently such a misalignment or warp between the inflow from larger scale bars within bars and the nuclear disc (e.g. middle-left or bottom-left cases), or a misalignment driven by the inflow of large clumps from the fragmentation of large-scale modes (e.g. top-left or top-centre cases).

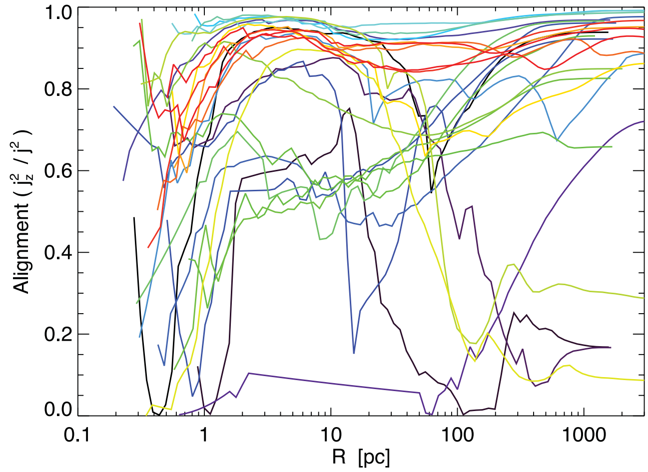

Figure 2. Alignment of the gaseous discs as a function of radius across our sample of simulations (each line is one simulation chosen near the peak in inflow). We quantify (mis)alignment as the ratio j_z^2/j^2, where j is the total angular momentum vector of the gas within an annulus around radius R and the z-axis is (by definition) the angular momentum axis of the entire galaxy. Within <10 pc, there is relatively weak correlation between the inner and outer disc angles.

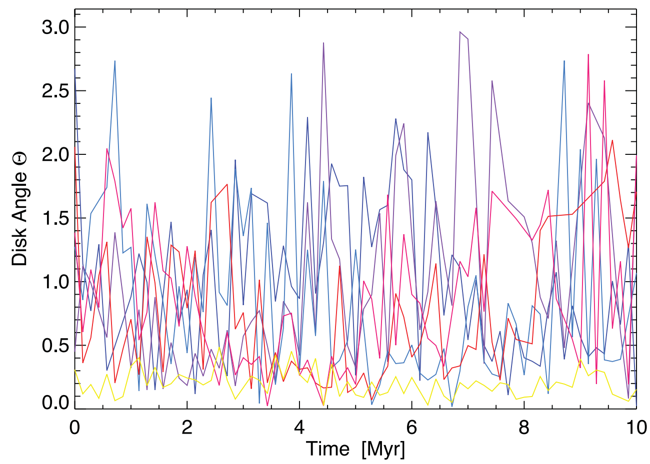

Figure 3. Polar angle Θ between the nuclear disc at our smallest resolved scale and the initial (uniform) angular momentum axis of the entire system as a function of time (same simulations as in Fig. 2; for clarity and to show short time-scale variability, we plot only a small fraction of the simulated time). The BHs here are accreting at $\sim$10 per cent of Eddington; at this rate, systems whose inflow angular momentum axis is effectively random over $\sim 10^7$ yr time-scales (the duration shown here) will be spun down to low/modest spin values; this includes most of our simulations. If they accrete at Eddington, the relevant time-scale is $\sim$Myr; this includes only the most rapidly variable simulations.

where the inflows from sub-kpc scale bars map on to the disc at the BH radius of influence, but with a very significant misalignment between the two.

Figs 2 and 4 quantify the degree of misalignment of the nuclear regions in the simulations. Since the observable quantity is generally the absolute value of the misalignment, we plot j_z^2/j^2 (i.e. $\cos^2\theta$), where j is the specific angular momentum in an annulus and the z-axis is the axis of the net angular momentum vector of the entire galaxy. Fig. 2 plots this as a function of radius at a given time in each simulation. Note that there are misalignments at all radii from $\sim$0.1 pc to $\sim$10 kpc (although the cases where there are significant misalignments on $>$kpc scales are generally galaxy mergers). Fig. 4 plots the cumulative distribution of this quantity at a fixed small radius, summed over all times and the entire ensemble of simulations. The misalignments on small scales are somewhere between pure random and pure alignment.

Fig. 3 illustrates the time evolution of the inflow axis. We plot the evolution of the central angular momentum orientation as a function of time: specifically the angle θ defined between $\boldsymbol{j}(t)$ (total angular momentum vector within five smoothing lengths of the BH – a couple pc) and the (fixed) z-axis (initial $\boldsymbol{j} = j\,\hat{z}$). Variation in ϕ (azimuthal angle) is much more rapid, but is less significant physically (since systems are axisymmetric to lowest order ϕ variation reflects lopsided/eccentric modes). There is large time variability. The most extreme cases exhibit several 'flips' with $\theta > \pi/2$ (anti-alignment of the disc with its original inclination).

Fully understanding how this affects the BH spin would require a number of sub-grid assumptions beyond the model here (see e.g. Fanidakis et al. 2011). Even if we assume that the gas retains its angular momentum axis below the resolution limit, we need to follow the orientation and magnitude of the BH spin as a function of time, which evolves as, at first, Lens–Thirring alignment forces the inner accretion disc to either align or anti-align (depending on whether

compared to our SPH smoothing. At $\sim$10 pc, the discs have scale heights from $\sim$1 to 3 pc compared to a softening of $\approx$0.3 pc, so the internal structure cannot be resolved at smaller radii. The true 'nuclear scale' re-simulations have resolution of $\approx$0.1 pc, and so resolve h/R to $\sim$1–3 pc.

$\boldsymbol{j}_{\rm disc} \cdot \boldsymbol{j}_{\rm BH} > 0$ or <0, respectively) inside of some warp radius $R_{\rm warp}$, and then the torques associated with this eventually re-orient the BH spin in alignment with the disc (Bardeen & Petterson 1975). For a given 'event', full alignment will occur if $\cos\theta > -J_{\rm d}/2J_{\rm BH}$ (where θ is the original angle between the BH and disc, $J_{\rm BH}$ is the BH spin angular momentum and $J_{\rm d}$ is approximately the interior disc angular momentum passing through the warp region; Scheuer & Feiler 1996; King et al. 2005). But this also depends on the substructure, dynamics and properties of the internal α disc, well below our best-case resolution (see Kumar & Pringle 1985). However, crudely speaking, for typical α-disc models, this translates to a criterion on the mass accreted in a given 'event' with coherent angular momentum: if the angular momentum remains coherent over a time-scale long enough for the BH to accrete some fraction (typically a few per cent; Lodato & Pringle 2006; Perego et al. 2009) of its mass, then the spin will re-orient to align (even if initially retrograde) and most of the accretion will go to spinning up the BH. If the inflow angular momentum is incoherent on this time/mass scale, however, the spin undergoes a random walk with decreasing magnitude (King & Pringle 2006; King, Pringle & Hofmann 2008). If the BH is accreting at a fraction λ times Eddington, this corresponds to a physical time-scale of $\sim\lambda^{-1}\,10^6$ yr. Consider this in Fig. 3. If the accretion is sufficiently rapid ($\lambda \approx 1$), then only the most extreme simulated variability will be sufficient to give very low spins. However, for the more typical $\lambda \approx 0.1$ (coherence time 10^7 yr) in observed systems (Kollmeier et al. 2006; Hickox et al. 2009; Hopkins & Hernquist 2009; Trump et al. 2009) and actually calculated (via the inflow rate into <0.1 pc) in these simulations, a large fraction of the simulations have sufficient resolved precession in their inflow angular momenta to produce a 'random walk' spin behaviour.

4 DISCUSSION

Using high-resolution simulations of gas inflows from galaxy to sub-pc scales around AGN, we study the evolution of BH–host galaxy alignments. We predict only a weak correlation between the nuclear axis and the large-scale disc axis. If anything, this is a lower limit to the typical degree of 'randomness' in alignment, as more clumpy star formation or infall from recycled stellar wind material can increase the variation in orientations. Twists and misalignments, therefore, can explain the random alignment of AGN discs relative to their host galaxies. A warped or twisted disc may also yield large covering angles towards the BH even when the disc itself is thin, although we argue in Hopkins et al. (2012a) that this is not alone sufficient to explain observed obscuration (the 'torus' must also be geometrically thick).

These misalignments occur for at least two reasons. First, there are cases where large-scale fragmentation occurs in the gas (part of a spiral arm or other instability fragments and sinks to the centre), which can dramatically change the nuclear gas angular momentum content (see also Nayakshin & King 2007; King, Pringle & Hofmann 2008; Levine, Gnedin & Hamilton 2010). And secondly, even in perfectly smooth flows, it is well known that secondary bars in the presence of dissipative processes (i.e. gas) will tend to decouple their angular momentum from the primary bar (e.g. Heller, Shlosman & Englmaier 2001, and references therein). Inflow and dissipation lead to runaway strengthening of the inner mode, which populates various chaotic orbit families and exchanges angular momentum with the outer mode, decoupling the inner mode angular momentum and orbit plane from that of the outer mode (Hasan & Norman 1990; Heller & Shlosman 1996; Maciejewski & Sparke 2000). The inner mode precesses or tumbles in three dimensions relative to the outer mode frame, a phenomenon seen in a large number of simulations (Shlosman & Heller 2002; El-Zant & Shlosman 2003; Englmaier & Shlosman 2004; Maciejewski & Athanassoula 2008) and observed double (and even triple) bars (Friedli & Martinet 1993; Shaw et al. 1995; Friedli et al. 1996; Erwin & Sparke 1999, 2002; Laine et al. 2002). These processes are common in our simulations, especially in the complicated triaxial potential of realistic merger-formed bulges.

An analogous process also occurs here with the inner lopsided disc at the inner radius [inner Lindblad resonance (ILR)] of the outer bar (itself, in several cases, the 'inner' of a double bar). Hopkins & Quataert (2011a) show in both these simulations and analytic calculations that angular momentum exchange in the gas in the central regions (inside the BH radius of influence but outside the viscous accretion disc) can be strongly dominated by supersonic gas shocks surrounding strong torquing regions in the stellar nuclear disc with lopsided/eccentric ($m = 1$) modes (see also Bacon et al. 2001; Jacobs & Sellwood 2001; Salow & Statler 2001; Sambhus & Sridhar 2002). These modes can resonantly exchange angular momentum with the pattern at larger radii in the manner of nested bars, leading (in plane) to possible reversals and counter-rotation of the pattern, which in turn reverses the sense of torques on the gas. If the mode is strong enough, the exchange in strong shock regions can be large enough to change the gas angular momentum by an order-unity factor. Generally, as the gas approaches the mode, it experiences a sudden, strong resonant torque, shortly followed by or accompanying a strong shock that dissipates its energy. When the torques are sufficiently strong, the gas falls in on a nearly radial orbit along the pattern; the small 'residual' angular momentum can have different signs depending on the instantaneous pattern speed, precession rate and resonance structure of the mode (all of which continuously evolve). Moreover, we show in Hopkins et al. (2012a) that when a sufficiently strong $m = 1$ mode appears, the inner disc becomes vulnerable to the 'firehose instability' and self-excites large vertical bending modes. The linear derivation of those modes therein suggests that they have both large growth rates and order-unity saturation amplitudes (i.e. they drive order-unity fluctuations in θ in Fig. 3); if there is a significant population of stars in the nucleus on retrograde orbits (from, say, previous accretion episodes), the growth rate and saturation amplitude of these modes are greatly enhanced (Sellwood & Merritt 1994; Davies & Hunter 1997). We should note that, although the evolution in Fig. 3 is extremely 'rapid' relative to e.g. secular processes at $>$kpc radii, it is still indeed secular: at 1 pc around a BH of $10^7-10^8\,{\rm M}_{\odot}$, 1 Myr represents $\sim$100$-$1000 dynamical times, so the relevant resonant effects can collectively operate over a very large number of orbital periods. All of these processes become more prominent as the nuclear gas is more strongly self-gravitating, so they may operate progressively more efficiently in higher accretion rate AGN. They do, however, rely on a complicated interaction between collisionless and collisional material; as such, many will not appear in simulations that do not include 'live' star formation in the disc (compare e.g. Colpi et al. 2007; Escala 2007). At least some observed AGN (with e.g. jets and maser mapping of their nuclear regions) appear to have such multiple misalignments corresponding to structures (nested bars) in their hosts (see e.g. Greenhill & Gwinn 1997).

We do not predict perfectly random alignments, as there is still some bias towards similar axes obvious in Fig. 4 (suggested in observations as well, in Battye & Browne 2009; Shen, Shao & Gu 2010; Lagos et al. 2011). Interestingly, there is also a suggestion in Figs 2 and 4 of a preference for misalignments of

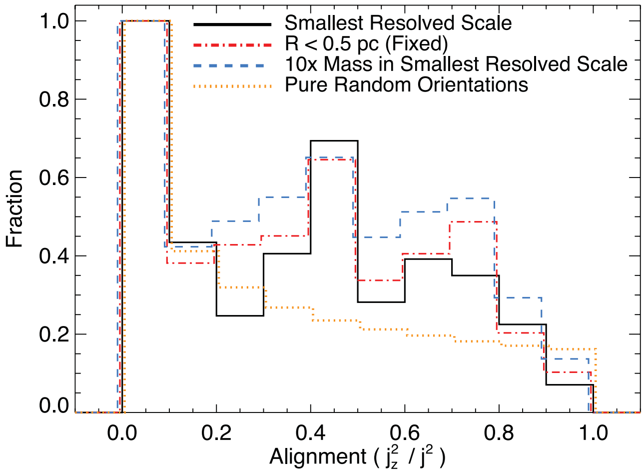

Figure 4. Distribution (averaged over time and over the ensemble of simulations) of the alignment/angle ($j_z^2/j^2 = \cos^2\theta$) between the nuclear disc and angular momentum axis of the large-scale system (where $j_z = j$, by definition). We measure this in three radii: the smallest resolved radius used in Fig. 3, a fixed physical radius of 0.5 pc and a radius enclosing 10 times the gas mass of that enclosed in the smallest resolved radius. The three agree reasonably well, suggesting that the results are robust at small radii (though this clearly reaches the limits of reliable resolution effects). To compare, we show the distribution which would be obtained if the orientations were purely random and uniformly distributed over the sky. Pure alignment would be a δ-function at $j_z^2/j^2 = 1$. The distribution is closer to random than to pure alignment; still, there is an obvious tendency for more alignment than in the pure random case. There may also be a weak excess of misalignments near $\cos^2\theta \sim 0.4{-}0.5$, but this is marginally significant.

$\cos^2(\theta) \sim 1/2$ ($\theta = (\pm\,\pi/4, \pm\,3\pi/4)$). These relative alignments reflect quasi-stable potential surfaces, for example, for an inner gas disc in a tumbling prolate quasi-spherical potential; they also form the backbone of ‘X-shaped’ (and some ‘peanut-shaped’) bulges formed by bar ‘buckling’ after the vertical motions are pumped by resonances in the presence of a nuclear mass concentration or secondary bar, like those seen here (Tohline & Durisen 1982; Pfenniger 1984; Pfenniger & Norman 1990). It is not surprising, then, that they form the upper envelope for the misalignments seen in the more ‘quiescent’ models here. The much larger misalignments seen in Fig. 2 and most dramatic ‘flips’ seen in Fig. 3, on the other hand, tend to arise from the action of large clumps/fragmentation.

This can have important implications for the spin evolution of BHs. If there are no further twists or clumpy structure beyond what is resolved here, the resulting spins will in some cases be maximal, but in a large fraction of our simulations would be modest – changes in alignment on sufficiently rapid time-scale will lead to rapid BH growth when the orbits are prograde, but then the growth suddenly drops when the orbits are retrograde, producing spins in the range $|a| \sim 0.1$–0.9 (see e.g. King & Pringle 2006). As these authors and others have noted, intermediate spins are interesting because they imply modest radiative efficiencies ($\epsilon \sim 0.05{-}0.2$, which may be favoured by BH luminosity density constraints; Wang et al. 2009) and reduce by a factor of several the fraction of maximal recoil ‘kicks’ with $\Delta v \gtrsim 1000\,\mathrm{km\,s^{-1}}$ in major BH–BH mergers (Kesden, Sperhake & Berti 2010; van Meter et al. 2010), although this depends on the orientation of the orbital angular momentum which may have preferred configurations (e.g. Bogdanović, Reynolds & Miller 2007), and is itself coupled to the accretion history and feedback efficiency in mergers (e.g. Dotti et al. 2010; Blecha et al. 2011). It has also been suggested that radio jet power may be modest except at near-maximal spins (e.g. Tchekhovskoy, Narayan & McKinney 2010).

If real BHs have very low spins, $|a| \lesssim 0.2$, some additional sub-grid processes are required beyond just what we resolve here. Either unresolved sub-grid clumpiness in the ISM that would lead to more ‘chaotic’ accretion by increasing the randomness of the disc orientations on small mass scales as individual clumps are accreted (King et al. 2008), or further twists/bends/misalignments continuing into the α disc (see e.g. Kinney et al. 2000; Greenhill et al. 2003; Kondratko, Greenhill & Moran 2005). There may also be resonant exchanges associated with the pairing process in BH mergers, some of which may be important to resolve the ‘last parsec problem’ (Colpi et al. 2007; Dotti et al. 2009; Nixon, King & Pringle 2011b; Nixon et al. 2011a). On the other hand, if near-maximal spins are the norm, then inflow is somewhat less random than what we find here; some other processes, such as slower, more extended accretion from low-density diffuse gas which is not gravitationally unstable, may dominate.

Misalignments can also have dramatic implications for BH feedback. An outer disc which is misaligned with the inner disc, especially the one which has multiple ‘twists’, presents a larger ‘working surface’ on which AGN feedback may couple (as opposed to an AGN in a single thin disc). Moreover, many feedback mechanisms are predicted to have preferential alignments corresponding to the spin or nuclear gas disc – radio jets and ionization cones being preferentially polar and broad absorption line winds being preferentially planar. If the inner disc precesses rapidly, these mechanisms might appear effectively isotropic to the gas at larger scales in the galaxy.

The results here are reminiscent of those of Barnes & Hernquist (1991, 1996) on somewhat larger scales. They found that the angular momentum of gas flowing into the nucleus of a merger remnant can lose its memory of the initial direction of the disc angular momentum.[3] On this basis, they argued that kinematically decoupled cores in elliptical galaxies may originate in this manner (Hernquist & Barnes 1991; Cox et al. 2006; Hoffman et al. 2010). In particular, frames from the animated sequences of their mergers (Barnes & Hernquist 1998) often display similarities to the images shown in Fig. 1.

The results here represent a first study of inflows in a relatively ‘smooth’ medium. In future work, we will extend the models here to include the effects of realistic stellar feedback, star formation and ISM structure, as well as more detailed physical models for AGN feedback. Stellar feedback should always be present in some form and may (as discussed above) further enhance the ‘randomness’ of the angular momentum on small scales. However, the microphysics of star formation and stellar feedback in the vicinity of even a quiescent BH, let alone a rapidly accreting QSO, is quite uncertain. AGN feedback is potentially important during phases of rapid accretion, but this is less clear – it may be that the effective duty cycle of strong feedback is such that it is not dynamically important for the angular momentum evolution of accreted material during the time when most of the mass is actually accreted (as, when it becomes strong, it suppresses subsequent accretion). This will, of course, depend on the specific feedback mechanisms. We also specifically avoid the BH–BH merger stage, choosing to focus instead on the more simplified case where there is a single BH in the galaxy nucleus. Certainly, ongoing pair merging may introduce additional misalignments (and will have important spin effects, noted above),

[3] On supergalactic scales, compare e.g. Bett & Frenk (2012).

but since misalignments are observed even in quiescent, isolated systems, their origin must be more general.

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