Jet-enhanced accretion growth of supermassive black holes

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ABSTRACT

We investigate the effect of a disc-driven jet on the accretion growth of cosmological supermassive black holes (SMBHs). The presence of a jet enhances the mass growth rate because for a given luminosity, the mass accretion rate, $M_\text{a}$, is higher (or equivalently, the radiative efficiency $\epsilon_\text{r}$ is lower for a fixed $M_\text{a}$) than that predicted by standard accretion disc theory. As jets carry away very little of the accreting matter, a larger proportion of the rest mass can reach the black hole during episodes of jet activity. We show quantitatively that the conditions required to grow a rapidly spinning black hole to a mass $\approx 10^9\, M_\odot$ by redshift $z \approx 6$, whilst satisfying the observational constraint $\epsilon_\text{r} \gtrsim 0.1$, are considerably less restrictive for jet-enhanced disc accretion than for standard disc accretion, which requires implausibly high super-Eddington accretion rates. Furthermore, jet-enhanced accretion growth offers a viable explanation for the observed correlation between black hole mass and radio loudness of quasars.

Key words: accretion, accretion discs – black hole physics – galaxies: evolution – galaxies: jets.

1 INTRODUCTION

The discovery of over 20 quasars at redshift $z \gtrsim 5.7$ (e.g. Fan et al. 2000, 2001, 2003, 2004, 2006; Goto 2006), with masses estimated to be $\gtrsim 10^9\, M_\odot$ (Barth et al. 2003; Vestergaard 2004; Jiang et al. 2006; Kurk et al. 2007), challenges our current understanding of the early Universe at the epoch of galaxy formation. The highest redshift quasar, Sloan Digital Sky Survey (SDSS) 1148+3251 (Fan et al. 2003), with $z \approx 6.43$ (corresponding to a cosmic time $t = 0.87$ Gyr assuming the standard $\Lambda$ cold dark matter (ΛCDM) concordance cosmology), is thought to harbour a black hole of mass $M_\text{a} \approx 10^9\, M_\odot$ (Barth et al. 2003; Fan et al. 2003; Willott, McLure & Jarvis 2003; Haiman 2004). This poses a significant constraint on viable black hole growth mechanisms.

In ΛCDM cosmology, dark matter haloes merge hierarchically with black holes merging and accreting in the gaseous centre (see e.g. Shapiro 2005; Volonteri & Rees 2005; Hopkins et al. 2006; Li et al. 2007). During mergers of host galaxies, the nuclear black holes can coalesce or be ejected due to gravitational wave recoil. Gravitational recoil does not significantly impede black hole growth if accretion is Eddington limited (Haiman 2004; Yoo & Miralda-Escude 2004; Volonteri 2007). Coalescence should produce a linear relation between the halo mass and the black hole mass (see e.g. Hachnelt, Natarajan & Rees 1998). However, the observed relation between the black hole mass and the bulge velocity dispersion of galaxies (Ferrarese & Merrit 2000) suggests instead that ongoing, sustained accretion, rather than coalescence as a result of mergers, is the primary process governing black hole growth.

An important constraint on accretion growth models is that the mean radiative efficiency $\epsilon_\text{r}$ must be sufficiently low to maximize the amount of matter accreted on to the black hole and minimize the amount of rest mass energy lost to radiation. However, the observed ratio of the quasar/active galactic nuclei (AGN) luminosity density to the local supermassive black holes (SMBH) mass density (at redshift $z \lesssim 5$) requires $\epsilon_\text{r} \gtrsim 0.1$ (Soltan 1982; Aller & Richstone 2002; Elvis, Risaliti & Zamorani 2002; Yu & Tremaine 2002; Marconi 2004). This is an empirical, model-independent lower limit. Since standard disc accretion on to a Schwarzschild black hole has a radiative efficiency $\epsilon_\text{r} \approx 0.06$ (Novikov & Thorne 1973), it has been argued (e.g. Elvis et al. 2002; Yu & Tremaine 2002; Barger et al. 2005) that the Soltan relation implies that quasars harbour Kerr black holes. Indeed, models of cosmological black hole evolution (Thorne 1974; Volonteri et al. 2005) and merger-driven accretion (di Matteo, Springel & Hernquist 2005), constrained by the evolution of the luminosity function of quasars (see e.g. Hopkins, Richards & Hernquist 2007), indicate that quasars undergo rapid spin-up. Furthermore, these models show that in order to grow cosmological black holes from an initial seed mass to that of a quasar by $z \gtrsim 3$, the amount of material accreted in a single accretion episode must be quite large. This acts to rapidly spin-up the black holes of massive high-redshift quasars (Volonteri, Sikora & Lasota 2007), contrary to the suggested low-spin scenario. We note, however, that models for low-spin black holes have also been proposed (King et al. 2005; King & Pringle 2006).

The radiative efficiency of a maximally spinning accreting black hole is $\approx 40$ per cent, which is too high to grow a SMBH by $z \approx 6$, unless implausibly high, super-Eddington accretion rates are invoked. Observations indicate that the dimensionless mass accretion rate, $\dot{m} \equiv L/L_\text{Edd}$, where $L_\text{Edd} = 4\pi G M_\text{a} m_p c / \sigma_T$ is the...
Observational constraints \( \approx z \) on accretion growth of cosmological, spinning SMBHs with the observational constraints \( \epsilon_r \geq 0.1 \) and \( m \approx 1 \). Mergers produce large-scale gravitational instabilities which can funnel gas down to the galactic core where it can be accreted (Mihos & Hernquist 1994a,b). In order for efficient disc accretion to proceed, another process must facilitate the transport of angular momentum on smaller scales. Numerical simulations demonstrate that the effective viscosity produced by magnetohydrodynamical turbulence, generated by the magnetorotational instability, is insufficient to account for the very high mass accretion rates inferred in the most powerful accreting sources, such as quasars (Hawley 2000; Hawley, Balbus & Stone 2001; Stone & Pringle 2001; Hawley & Balbus 2002; King & Pringle 2007), unless a large scale, systematic poloidal field is present in the accretion flow (Steinacker & Henning 2001; Campbell 2003; Kigure & Shibata 2005; Salmeron, Konigl & Wardle 2007). In this case, a magnetized jet forms and the overall mass accretion rate increases considerably as a result of enhanced angular momentum transport and negligible mass loss (Kuncic & Bicknell 2004, 2007a,b). This creates auspicious conditions for efficient mass growth of black holes.

Approximately 60 per cent of all AGN display outflow phenomena (Ganguly 2007). Relativistic outflows, in particular, are a characteristic feature of accreting SMBHs. X-ray observations of galaxy clusters indicate that substantial amounts of mechanical energy may be deposited into the intracluster medium by powerful AGN jets (see e.g. Birzan et al. 2004; Allen et al. 2006; Fabian et al. 2006; Rafferty et al. 2006; Taylor et al. 2006). If some fraction of the total accretion power is converted to jet kinetic power, then \( \epsilon_j \) is lower than that predicted by standard disc accretion for a given \( M_a \). Hence, the black hole growth rate for jet-enhanced accretion is larger. Existing accretion growth models simply set the total accretion efficiency \( \epsilon_a \) equal to the radiative efficiency \( \epsilon_r \) and thereby do not take into account the conversion of accretion power into non-radiative form (e.g. mechanical energy). Relativistic jets, in particular, can carry away a substantial amount of kinetic power but very little mass. Furthermore, the positive correlation between radio loudness and black hole mass (Laor 2000; Lacy et al. 2001; McLure & Dunlop 2002; Oshlack, Webster & Whiting 2002; Woo & Urry 2002; Dunlop et al. 2003; Marziani et al. 2003; Shields et al. 2003; McLure & Jarvis 2004; Liu, Jiang & Gu 2006; Metcalf & Magliocchetti 2006) suggests that jet-enhanced accretion growth results in more massive black holes.

In this paper, we quantitatively determine the effect of jet-enhanced accretion on the cosmological growth of SMBHs. In Section 2, we present results for a jet-enhanced accretion growth model. We discuss the implications of these results in Section 3, and give concluding remarks in Section 4.

## 2 Jet-Enhanced Accretion

The black hole mass growth rate is given by (see e.g. Shapiro 2005)

\[
\frac{dM_a}{dt} = (1 - \epsilon_a) M_a, \quad (1)
\]

where \( \epsilon_a \) is the total accretion efficiency and \( M_a \) is the black hole mass. The efficiency of conversion of rest mass energy to radiation is

\[
\epsilon_r = \frac{L}{M_a c^2}, \quad (2)
\]

where \( L \) is the luminosity. Existing accretion growth models simply set \( \epsilon_r = \epsilon_a \) and hence do not take into account the conversion of accretion power into non-radiative forms, such as kinetic power in a relativistic jet. The total accretion efficiency should thus be more accurately expressed as

\[
\epsilon_a = \epsilon_r + \epsilon_j, \quad (3)
\]

where \( \epsilon_j \) is the jet efficiency (see Jolley & Kuncic 2008).

Accretion power can be converted to jet power via a magnetic torque that acts over the disc surface and vertically transports angular momentum and energy from the disc (Kuncic & Bicknell 2004). The rate at which work is done against the disc by the magnetic torque is (Jolley & Kuncic 2008)

\[
P_j = \frac{3}{2} c \int_0^\infty f_1(r) \left[ \int_{r_i}^{r_f} f_2(r) B_z B_r \, dr \right] \, dr, \quad (4)
\]

where \( f_1(r) \) and \( f_2(r) \) are dimensionless functions of the disc radius, \( r_i \) is the innermost stable orbit, and \( B_z \) and \( B_r \) are the azimuthal and vertical components of the magnetic field, respectively. Note that a large-scale poloidal field is required to produce jets in numerical simulations (e.g. Steinacker & Henning 2001; Campbell 2003; Kigure & Shibata 2005).

A non-zero \( \epsilon_j = P_j/M_a c^2 \) can enhance accretion growth because jets transport angular momentum and thus give rise to a higher mass accretion rate (Kuncic & Bicknell 2004). For a fixed \( \epsilon_j \) (or a fixed \( L \)), this means that \( \epsilon_a \) is lower. The accretion efficiency \( \epsilon_a \) for a relativistic disc (Novikov & Thorne 1973) evolves with the dimensionless spin \( a = J/M_a \) of the black hole, where \( J \) is the specific angular momentum. The large amounts of material that must be accreted to form a \( z > 3 \) quasar leads to very rapid spin-up of a black hole (Volonteri et al. 2007). Thus, we take the spin \( a \) and, hence, the accretion efficiency \( \epsilon_a \), to be approximately constant with time. If the average radiative efficiency and hence, average \( \epsilon_j \) are also approximately constant, then the time evolution of black hole accretion growth is

\[
M_a(t) = M_a(t_0) \exp \left[ \frac{(t - t_0)(1 - \epsilon_j)}{\epsilon_r} 4\pi G m \frac{M_a}{\sigma_T c m} \right], \quad (5)
\]

where \( M_a(t_0) \) is the initial mass of the black hole. Cosmological simulations suggest seed black holes with \( M_a(t_0) \approx 600 M_\odot \) at \( z \approx 25 \) (Madau & Rees 2001; Omukai & Palla 2003; Yoshida et al. 2003).

Fig. 1 shows the dependence of the final mass of a black hole on the fraction of accretion power removed by a jet for different values of the spin \( a \) and Eddington ratio \( \dot{m} \). Standard disc accretion, which neglects vertical transport of angular momentum and energy by magnetized jets, corresponds to the case \( \epsilon_j/\epsilon_a = 0 \). The presence of a jet results in a higher final black hole mass than the standard disc accretion model. The shaded regions in Fig. 1 indicate values of \( \epsilon_j/\epsilon_a \) where \( \epsilon_j \geq 0.1 \), as implied by observations of the ratio of the AGN and quasar luminosity density to the SMBH mass density (Soltan 1982). Fig. 1 shows that in order to grow a SMBH of mass \( M_a \approx 10^6 M_\odot \) by \( z \approx 6 \), a standard disc (\( \epsilon_j/\epsilon_a = 0 \)) requires a low spin, \( a < 0.75 \), or highly super-Eddington accretion, \( \dot{m} \approx 2 \). The presence of a jet significantly relaxes these constraints: Eddington-limited accretion can grow a rapidly spinning (with \( a = 0.98 \)) black hole to \( M_a \approx 10^6 M_\odot \) by \( z \approx 6 \) and maintain a radiative efficiency \( \epsilon_r \approx 0.1 \) if there is a jet that removes two-thirds of the accretion power.

Fig. 2 shows the black hole accretion growth evolution as a function of \( z \) for \( 25 \geq z \geq 6 \) for different values of \( \dot{m} \) and \( a \). The solid
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Figure 1. The effect of jet-driven accretion on the final mass of a black hole at $z = 6$ growing from an initial mass $M_\odot (t_0) = 600 M_\odot$ at redshift $z = 25$ for different values of the dimensionless spin $a$ and corresponding accretion efficiency $\epsilon_a$, as shown. The parameter $\epsilon_j/\epsilon_a$ is the fractional accretion power removed by a jet. The solid line is for an Eddington ratio $m = 2$, the dotted line is for $m = 1$ and the dashed line for $m = 0.5$. The shaded areas indicate regions where the radiative efficiency is $\epsilon_j \gtrsim 0.1$.

curves are for jet-enhanced accretion growth with the largest possible fractional jet power $\epsilon_j/\epsilon_a$, corresponding to $\epsilon_j = 0.1$. The dotted curves correspond to accretion growth via a standard disc (i.e. $\epsilon_j = 0$). The shaded region indicates where $\epsilon_j \gtrsim 0.1$. Jet-enhanced accretion growth is evident in all cases, with the most enhancement occurring at high $a$ and $m \gtrsim 1$. Note that for plausible physical parameters, black holes cannot grow to masses $\approx 10^9 M_\odot$ by $z = 6$ for sub-Eddington accretion rates even in the case of jet-enhanced accretion (Fig. 2: left-hand side column).

For Eddington-limited accretion (Fig. 2; middle column), a black hole of $\approx 10^9 M_\odot$ at $z = 6$ can be formed for jet-enhanced accretion (solid line) provided $a \lesssim 0.95$. By comparison, standard disc accretion at the Eddington rate (dashed line) requires an even lower spin $a \lesssim 0.75$, which is difficult to reconcile with the rapid spin evolution of high-redshift quasars (Volonteri et al. 2007). For super-Eddington accretion with $m = 2$ (Fig. 2; right-hand side column), standard disc accretion still requires the spin to be below 0.95 to grow a $10^9 M_\odot$ black hole by $z \approx 6$, whereas jet-enhanced accretion achieves this for all spins up to $a = 0.999$. Clearly, the presence of a jet can substantially relax the requirements for growing cosmological SMBHs. The rapid evolution of black holes to a near-maximal spin (Thorne 1974; Volonteri et al. 2005) poses a serious problem to standard disc accretion, which cannot grow high-spin SMBHs rapidly enough without invoking implausibly high super-Eddington accretion rates. For example, $m = 4$ is required by the standard model to grow a $M_\odot \approx 10^9 M_\odot$ black hole with $a = 0.999$ by $z = 6$. Jet-enhanced accretion requires just $m = 1.3$, with two-thirds of the accretion power in this case used to power a jet, thereby reducing the radiative efficiency to $\epsilon_j = 0.1$.

3 DISCUSSION

The presence of a jet can greatly enhance the black hole mass growth rate because for a given mass accretion rate, the radiative efficiency is lower than that of a standard disc. Or equivalently, the accretion rate is higher for a given luminosity. This arises because jets enhance angular momentum transport; the additional accretion power, which depends on the accretion rate, drives the jet. An important constraint for jet-enhanced accretion growth of black holes is the average jet efficiency over the lifetime of the rapid growth phase ($\Delta t \approx 0.7$ Gyr). Recent studies (see e.g. Binney, Bibi & Omma 2007; Körding, Jester & Fender 2008) suggest relativistic jets can remove well in excess of half the total accretion power (i.e. $\epsilon_j/\epsilon_a \gtrsim 50$ per cent), implying they are an ‘all or nothing’ phenomenon. When combined with the estimated $\approx 18$ per cent duty cycle for quasar activity for $M_\star \gtrsim 10^9 M_\odot$ and $z \gtrsim 2$ (see Wang, Chen & Zhang 2006, and references therein), this suggests a lower limit to the fractional jet power of $(\epsilon_j)/\epsilon_a \gtrsim 10$ per cent. For a black hole with $a = 0.99 (\epsilon_a \approx 0.29)$, this gives $(\epsilon_j) \gtrsim 0.03$, consistent with the value independently derived by Heinz, Merloni & Schwab (2007).

This implies that, on average, accreting black holes liberate most of their energy in the form of radiation rather than jet kinetic energy. However, black holes grow faster during jet-active phases because
mass accretion is enhanced and we argue that such rapid growth episodes are necessary to explain the most massive cosmological black holes.

If the quasar duty cycle extrapolates to high \( z \), then we predict jet-enhanced accretion to grow a \( \approx 10^9 \, M_\odot \) black hole by \( z \approx 6 \) for \( \bar{m} \gtrsim 10^2 \). For comparison, standard disc accretion would require an accretion rate that is at least 30 per cent higher. Furthermore, this may be an overly conservative estimate if jets were more prevalent at high \( z \) and hence, the quasar activity duty cycle was higher. Existing data suggest that jets were indeed more common at \( z \approx 2 \) than today, but the radio luminosity function at \( z \gtrsim 2 \) is still not well constrained (see e.g. Liu & Zhang 2007; Willott et al. 2001).

For a \( \approx 10^7 \, M_\odot \) accreting black hole with \( a = 0.99 \) (\( \epsilon_a \approx 0.29 \)) and \( \langle \epsilon_j \rangle = 0.03 \), the average accretion rate needed to produce a luminosity \( L = 3 \, L_{\text{edd}} \approx 4 \times 10^{47} \, \text{erg \, s}^{-1} \) with an average radiative efficiency \( \langle \epsilon_r \rangle = 0.26 \) is \( \approx 25 \, M_\odot \, \text{yr}^{-1} \). The average jet power is \( \langle P_j \rangle \approx 4 \times 10^{46} \, \text{erg \, s}^{-1} \), which agrees well with jet kinetic powers inferred observationally (e.g. Merloni & Heinz 2007; see also Celotti & Ghisellini 2008 for \( a \approx 0.5 \)). As jets have radiative efficiencies typically \( \lesssim 1 \) per cent (see e.g. Merloni & Heinz 2007), virtually all the kinetic energy is deposited into the ISM or ICM. Over the rapid growth phase (\( \Delta t \approx 0.7 \, \text{Gyr} \)), the average total energy deposited is \( \langle P_j \Delta t \rangle \approx 10^{53} \, \text{erg} \). This is consistent with the strong lower limit of \( 10^{50} \, \text{erg} \) inferred from X-ray cavities in rich cluster cores (Birzan et al. 2004; Binney et al. 2007).

Finally, we can check whether spinning accreting black holes in AGN remain consistent with observations of the X-ray background (XRB) by matching the expected mass density of relic black holes deduced from the XRB (see Marconi 2004, and references therein),

\[
\rho_{\text{XRB}} = (4.7-10.6) \times \left( \frac{1 - \langle \epsilon_r \rangle}{9 \langle \epsilon_j \rangle} \right) \times 10^5 \, M_\odot \, \text{Mpc}^{-3}
\]

to the local black hole mass density \( \rho_{\text{BH}} = (4.4-5.9) \times 10^5 \, M_\odot \, \text{Mpc}^{-3} \) (Graham & Driver 2007). Marconi (2004) show that \( \rho_{\text{XRB}} \) is compatible with \( \rho_{\text{BH}} \) without requiring radiative efficiencies considerably higher than \( \approx 0.1 \). Although they used an earlier estimate of \( \rho_{\text{BH}} \) with a slightly broader range, their result still holds for the more restrictive range deduced by Graham & Driver (2007). However, as pointed out by Marconi (2004), if some of the accretion energy emerges in non-radiative (i.e. mechanical) form (i.e. \( \epsilon_a \neq \epsilon_j \)),

Figure 2. The black hole mass evolution as a function of redshift. The left column is for the case \( \bar{m} = 0.5 \), the middle column is for \( \bar{m} = 1 \), and the right column is for \( \bar{m} = 2 \). The top row is for a dimensionless spin \( a = 0.750 \) (corresponding to an accretion efficiency \( \epsilon_a = 0.12 \)), the second row is for \( a = 0.950 \) (\( \epsilon_a = 0.20 \)), the third row is for \( a = 0.990 \) (\( \epsilon_a = 0.29 \)) and the bottom row is for \( a = 0.999 \) (\( \epsilon_a = 0.39 \)). The solid line corresponds to the maximum possible value of \( \epsilon_j/\epsilon_a \) such that \( \epsilon_t = 0.1 \), and the dotted line is the case without a jet i.e. \( \epsilon_j/\epsilon_a = 0 \) and \( \epsilon_t = \epsilon_a \). The shaded areas indicate regions where the radiative efficiency is \( \epsilon_j \gtrsim 0.1 \).
then it is possible to place some constraints on the mean accretion efficiency $\langle \epsilon_a \rangle$ and thereby the mean spin of accreting black holes in the AGN population. We do not expect the mean black hole spin across the whole AGN population to be necessarily as high as that of the high-$z$ population. Indeed, $\rho_X M_{\text{BH}}$ and $\rho_B$ can be compatible with each other and with the Soltan relation, $\langle \epsilon_a \rangle \gtrsim 0.1$, if the mean accretion efficiency in the AGN population is $\langle \epsilon_a \rangle \lesssim 0.2$, corresponding to black hole spins $a \lesssim 0.95$. This also implies $\langle \epsilon_a \rangle \lesssim 0.1$ and since this is comparable to the mean jet efficiency we deduced at high $z$, it suggests a fundamental jet production mechanism that remains remarkably the same across the entire accreting SMBH population.

4 CONCLUSIONS

High-redshift accreting black holes are rapidly spinning and produce an enormous amount of power. The ubiquity of jets and outflow phenomena amongst accretion-powered sources provides clear evidence that not all of the accretion power is radiated away, as predicted by standard accretion disc theory. That is, for a given luminosity, the mass accretion rate of sources with jets is higher than that of sources without jets. This is because jets enhance angular momentum transport while minimizing mass loss. We have shown that the conditions required to grow a rapidly spinning black hole to a final mass $\approx 10^9 M_\odot$ by $z \approx 6$ are considerably more easily met for jet-enhanced disc accretion than for standard disc accretion. Our results indicate that while accreting black holes, on average, liberate most of their energy in radiation, the most massive cosmological black holes may undergo rapid growth episodes associated with enhanced rates of mass accretion driven by intermittent jet activity. This is consistent with the observed correlation between radio loudness and black hole mass in AGN. It also implies that jets may have provided an important means of angular momentum and energy transport in the high-redshift Universe.

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