Abstract. There is growing interest in the possible link between the growth of supermassive black holes and the effect of feedback from them on galaxy growth. There are three areas of significant uncertainty: (i) the physics of the feedback; (ii) the prevalence and effectiveness of feedback; (iii) the link between the growth of black holes and their hosts. The 2QZ optical QSO survey indicates that luminous QSOs are relatively short-lived, and it has recently been shown that the observed bolometric luminosity density from all AGN and its evolution can be reproduced if black holes grew coevally with their galaxies, implying but not requiring a causal link between galaxy growth and black hole growth. At low redshifts there is some evidence that black hole and galaxy growth are starting to decouple.

1. Introduction

For many years the active galaxy phenomenon was regarded as an interesting sideline in astrophysics that related solely to our understanding of black holes. However, with the recognition that every massive galaxy in the local universe has a supermassive black hole at its heart (Magorrian et al. 1998; Richstone et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000) we now recognise that black hole formation is an integral part of galaxy formation, with relationships between black hole and host galaxy that are consistent for galaxies with or without AGN (Onken et al. 2004; Barth, Greene & Ho 2005). Moreover, it now seems possible that feedback from black hole growth may have a significant effect in shutting off star formation and defining the colour-luminosity distribution of massive galaxies (Benson et al. 2003; Croton et al. 2006; Bower et al. 2006; De Lucia et al. 2006). However, our understanding of both the physics and the prevalence of AGN feedback is extremely limited, as reviewed in the next section. We also have only a partial understanding of the cosmological dependence of black hole growth within galaxies, yet if we wish to understand AGN feedback in the cosmological context this is surely a crucial aspect of the problem. In later sections of this article I discuss one particular scenario for black hole growth, namely that black holes and galaxies and their dark halos grow coevally, and compare with observation.

2. AGN feedback - fact or fiction?

The physics of supermassive black hole growth in galaxies and its cosmological evolution has recently been receiving wide attention because of the pos-
sible effects of AGN feedback on the formation of the host galaxy itself (e.g. Di Matteo et al. 2005). Since we now recognise that every massive galaxy (at least) has a black hole, such feedback may be an integral part of the general galaxy-formation process. Benson et al. (2003) have argued that something like AGN feedback is required to shut down star formation in the most massive galaxies in order to recreate the observed galaxy mass function, and it has been argued that such feedback is required to reproduce the observed colour-luminosity distribution of galaxies (Bower et al. 2006; Croton et al. 2006; De Lucia et al. 2006). However, the feedback process has to operate in every galaxy and in the relatively recent universe, so rather than feedback from the luminous QSO or AGN phase of black hole growth, these authors envisage a “radio mode” in which a radiatively-quiet, but kinetically-powerful, jet or outflow provides the feedback in the recent universe.

It has long been suggested that radio sources may provide significant heat input to cluster gas (e.g. Miller 1988; Pedlar et al. 1988, 1990) but this idea wasn’t really taken seriously until the discovery both of a lack of cooling gas in “cooling flow” clusters and of a possible link with radio structures in massive clusters such as Perseus (Peterson & Fabian 2006 and references therein). But most galaxies at the present day don’t have powerful radio sources associated with them, so we need to consider the evidence for “quiet” outflows in nearby galaxies.

Nearby Seyfert active galaxies do have low density outflowing gas in their nuclear regions, but so far these do not appear energetically significant: in NGC 5548 for example the mass outflow rate is $\dot{M} \sim 0.3 \, M_\odot \, \text{year}^{-1}$ with a maximum outflow velocity $\sim 1000 \, \text{km} \, \text{s}^{-1}$ (Steenbrugge et al. 2005), so it seems unlikely that this amount of feedback would significantly affect the host galaxy. Evidence for higher velocities and therefore significantly higher mass and momentum outflow rates has been seen in a few QSOs (e.g. Pounds et al. 2003). High velocity QSO outflows are also seen in UV absorption lines, occurring in $\sim 26$ percent of QSOs (Trump et al. 2006), and it has been supposed that these might be associated with an energetic disc wind (e.g. Proga & Kallman 2004), but if such outflows are restricted to the rare (at $z = 0$) luminous QSO phase of black hole activity they won’t do the job. But kinetic jet output may be more significant than outflowing winds (e.g. Omma & Binney 2004), and radiatively-inefficient flows may produce such outflows (Narayan & Yi 1994; Ho 2002), or indeed rotating black holes may produce output electrodynamically (Blandford & Znajek 1977; Reynolds 2006) perhaps independently of visible radiation. But a requirement of all these pictures is that, regardless of whether or not we can see it, the source of the feedback energy is gravitational - accretion of matter onto the black hole. Despite many attempts over the past four decades, we still have limited understanding of how black holes form in galaxies and why their luminous accretion phase shows such strong cosmological evolution. In the remainder of this article we discuss what we know about black hole accretion and its cosmological history, and in particular discuss the hypothesis that black holes and galaxies grew coevally.
3. QSO and AGN evolution

Twenty years ago a striking picture emerged of the cosmological evolution of luminous QSOs: they had an optical luminosity function that had a broken power-law form and that evolved steadily to lower luminosity at lower redshifts without changing in normalisation (Marshall et al. 1983; Boyle et al. 1988). A natural interpretation of this was that supermassive black holes formed relatively early in the universe, and that accretion onto them steadily declined with time to produce the apparent “pure luminosity evolution”. More recently however this picture has fallen into disfavour, for two reasons.

First, it is widely believed that dark matter haloes and their galaxies have grown hierarchically, with massive structures continuing to build up in the relatively recent universe. It is often hypothesised that QSOs are triggered by mergers between galaxies in such a hierarchical universe, and models seeking a cosmological explanation for QSO evolution have been based on a merger-driven build-up of black holes (e.g. Kauffmann & Haehnelt 2000). This link to galaxy build-up would explain the qualitative similarity in the cosmological evolution of star formation and nuclear black hole activity (e.g. Dunlop 1997; Boyle & Terlevich 1998; Percival & Miller 1999).

Second, a more detailed look at the luminosity function has revealed departures from pure luminosity evolution, with evolution in the slope of the luminosity function at both bright and faint magnitudes (Hewett, Foltz & Chaffee 1993; Goldschmidt & Miller 1998; Hopkins et al. 2006; Fan 2006). More significantly, it seems that the peak in the comoving space density of AGN/QSOs of a given luminosity shifts systematically to lower redshifts with decreasing luminosity (Steffen et al. 2003, Cowie et al. 2003, Ueda et al. 2003, Zheng et al. 2004; Barger et al. 2005, La Franca et al. 2005, Hasinger, Miyaji & Schmidt 2005, and Hopkins, Richards & Hernquist 2006), a phenomenon that has become known as cosmic downsizing. The downsizing is often interpreted as reflecting an increasing prevalence of lower-mass black hole growth with decreasing redshift (but note that, unlike the case of galaxy downsizing, the black hole masses are not well determined at the redshifts covered by the above surveys, so this interpretation can only be regarded as preliminary).

Despite these concerns, the basic picture of twenty years ago must nonetheless be correct: the comoving irreducible mass in black holes cannot decrease with cosmic time, so the decrease observed in the integrated AGN luminosity density (and in the differential luminosity function) must indeed arise from a mean accretion rate that decreases with cosmic time. The departures from pure luminosity evolution are then most likely indicating that we are not observing a single fixed population of long-lived black holes but rather the statistical changes in a relatively (compared to the Hubble time) short-lived population.

Confirmation that luminous QSO lifetimes are shorter than the Hubble time comes from measurement of their clustering properties: the lack of clustering growth to lower redshift shows that QSOs cannot be a long-lived population of objects (Croom et al. 2005, these proceedings). The upper limit on their mean lifetime is redshift dependent and does depend on the bias model assumed for QSOs, but a reasonable model yields $2\sigma$ limits on their existence within the 2QZ survey of $< 2$ Gyr and $< 1$ Gyr at $z = 1$ and $z = 2$ respectively.
Hence the picture that now emerges is that AGN evolution must be caused by a decline in overall accretion rate onto black holes, but with a characteristic timescale that indicates a cosmological influence on a population of objects whose active lives are short. We can measure the characteristic timescale for the QSO population change from the optical luminosity function. If the characteristic break luminosity, \( L^* \) varies as \((1 + z)^\gamma\), then the characteristic timescale may be expressed as

\[
\tau \equiv \frac{L^*}{|dL^*/dt|} = \frac{1 + z}{\gamma dz/dt} = \frac{1}{\gamma H(z)}
\]

where for the optical LF, \( \gamma \approx 3 \). In the next section we see whether a cosmological origin for this timescale can be identified.

4. The dark halo accretion rate

The growth of dark halos can be calculated within the framework of hierarchical growth using the extended Press-Schechter (Lacey & Cole 1993, 1994) approach (Miller et al. 2006). The timescale for growth of halos of mass \( M_H \) is

\[
\tau_H \equiv \frac{M_H}{|dM_H/dt|} = \frac{1}{f(M_H)|d\delta_c/dt|},
\]

where \( f(M_H) \) is a slowly-varying function of mass, of order unity, and where \( \delta_c \) is the usual Press-Schechter redshift-dependent critical overdensity for collapse (see Miller et al. 2006 for full details). For an Einstein-de-Sitter universe this has a simple form,

\[
\tau_{H,\text{EdS}} = \frac{1}{1.68f(M_H)H(z)(1 + z)},
\]

which has a similar value at \( z \sim 1 \) to that observed in the QSO luminosity function. The timescale is insensitive to the choice of cosmology. It is tempting then to suppose that the timescales for black hole growth and dark halo (and hence galaxy) growth are comparable and perhaps related.

5. Coeval evolution of black holes and their hosts

One of the striking features of the black hole/bulge \( M - \sigma \) relation in the local universe is its remarkably small scatter, with an intrinsic dispersion no larger than \( \sim 0.3 \) dex (Tremaine et al. 2002). It seems likely that feedback between black hole and galaxy growth is required to produce such a tight relation (e.g. King 2005), but whatever the mechanism it seems most natural to suppose that the black hole has acquired its mass at the same time as the galaxy has acquired its mass: i.e., that black holes and galaxies have grown coevally. Miller et al. (2006) have investigated the hypothesis that the timescales for black hole and galaxy growth are the same and show the same cosmological dependence. The hypothesis is that, averaged across all galaxies at any given cosmological epoch,

\[
\tau_{BH}(z) \equiv \frac{M_{BH}}{|dM_{BH}/dt|} = \frac{M_H}{|dM_H/dt|} \equiv \tau_H(z),
\]
Figure 1. The AGN bolometric luminosity density deduced from the best-fit model of Ueda et al. (2003), integrating over the range $10^{40} < L_X < 10^{48}$ erg s$^{-1}$ and applying the bolometric correction of Marconi et al. (2004) and correction for Compton-thick AGN of Ueda et al. (solid curve). Also shown are uncertainties estimated from refitting to the binned data of Ueda et al. (points with error bars: horizontal bars indicate the range of redshifts included in each point). The luminosity density expected in PCE is shown for two cases: (i) no evolution in the comoving black hole mass density (dot-dashed upper curve); (ii) evolution in the comoving black hole mass density that tracks the evolution of massive dark halos with $M_H > 10^{11.5} \, M_\odot$ (dashed curve). Both curves assume average radiative efficiency $\langle \epsilon \rangle = 0.04$.

where $M_{BH}$ and $M_H$ are the mass of a black hole and its dark halo respectively. We call this “Pure Coeval Evolution” (PCE). The hypothesis does not require there to be a direct causal link between the two, but it may be that feedback processes drive the system towards this behaviour.

There are two key predictions of this hypothesis. First, the mean Eddington ratio of black hole accretion, averaged over all galaxies, should rise dramatically to high redshifts, as shown in Babič et al. (these proceedings). Note that at any given epoch there is expected to be a wide range of individual Eddington ratios: galaxies with the highest values, close to unity, would be those recognised as AGN or QSOs. If Eddington ratios do have an upper bound around unity, we do not expect the Eddington ratio of the most luminous AGN to show much cosmological evolution (see Kollmeier et al. 2006). Less luminous AGN and normal galaxies may show evidence for such evolution, however (Netzer & Trakhtenbrot 2006). Averaged over all galaxies, not just AGN, the mean Eddington ratio should increase at higher redshift, implying a greater prevalence of visibly accreting black holes at higher $z$.

Second, we can predict the expected bolometric output from accreting black holes, as follows. The integrated bolometric luminosity density $\rho_L$ produced by AGN depends on the number density of black holes, on the mean accretion rate
onto those, and on the mean radiative efficiency $\langle \epsilon \rangle$. If we adopt the simplest assumption, that equation \[\] applies on average to black holes of all masses, and if we approximate the function $f(M_H)$ as being independent of mass (see \[\]) then we can write

$$
\langle \rho_L \rangle \simeq c^2 \rho_{BH} \left( \frac{\epsilon}{(1 - \epsilon)} M_{BH} \right) \left( \frac{dM_{BH}}{dt} \right)
$$

$$
\simeq c^2 \rho_{BH} \left( \frac{\epsilon f(M_H)}{1 - \epsilon} \right) \left( \frac{d \delta_c}{dt} \right),
$$

(2)

where $\rho_{BH}$ is the cosmic black hole mass density. Here we adopt the value for $\rho_{BH}$ at $z = 0$ estimated by \cite{Marconi2004}. The result of this calculation is shown in Fig.\[\] for two different assumptions. The dot-dashed curve shows the expected evolution if $\rho_{BH}$ does not change with redshift: the dashed curve shows the expected evolution if $\rho_{BH}$ tracks the mass density in massive halos, $M_H > 10^{11.5} M_\odot$, calculated from the EPS mass function. We see remarkably good agreement with the evolution in bolometric luminosity density, derived from hard X-ray surveys (solid curve and points with error bars), if the mean radiative efficiency has a constant value $\langle \epsilon \rangle \simeq 0.04$. This is a promising result: there is no other free normalisation of the predicted luminosity density, and the value of $\langle \epsilon \rangle$ required matches very well both theoretical expectation ($\epsilon \lesssim 0.06$ for accretion onto a Schwarzschild black hole) and determinations based on a comparison of the X-ray background and the local relic black hole mass density (e.g. \cite{Marconi2004}).

We can however also see that the prediction is too high at $z < 0.5$, overproducing the bolometric luminosity density by a factor 2 at $z = 0$. This implies that black hole growth and halo/galaxy growth have decoupled by the present day. This result may well be related to the phenomenon of downsizing noted at $z = 0$ by \cite{Heckman2004}. In that work it appears that the mean Eddington ratio becomes a function of mass, a result that also appears to be confirmed by \cite{Netzer2006}. Possible physical causes of decoupling could be that either it is an apparent effect caused by a decrease in radiative efficiency at low Eddington ratios (e.g. \cite{Narayan1995, Beckert2002}), or that black hole growth really does slow down as a result of the changing environments of galaxies towards $z = 0$, with an increasing prevalence of galaxies forming into groups and clusters.

6. Conclusions and further thoughts

It seems that the hypothesis of Pure Coeval Evolution of black holes and dark halos reproduces rather well the observed bolometric luminosity density produced by AGN at $z < 3$, implying that, broadly-speaking, black holes and their hosts grow together. The dramatic decrease in AGN activity towards $z = 0$ is thus seen to be a result of the slow-down in growth of galaxies themselves. This parallel evolution does not necessarily imply a direct causal link between them, but it is attractive to invoke such a causality, especially as this would also help explain the very tight $M - \sigma$ relation between black holes and their hosts in the local universe (\cite{Tremaine2002}).
One of the main successes of this hypothesis is that it reproduces the observed bolometric luminosity density assuming a very reasonable value for the mean radiative efficiency, \( \langle \epsilon \rangle \simeq 0.04 \) - no previous model of AGN evolution has been able to predict the absolute value of the luminosity density. It is worth noting that Pure Coeval Evolution produces a better match to the luminosity density evolution than current generations of semi-analytic models (e.g. \cite{Croton2006}).

A factor-two decoupling between black holes and galaxy/halo growth does seem to occur at low redshift, more measurements of Eddington ratio as a function of black hole mass, environment and redshift should enable us to distinguish alternative explanations for this effect.

More observational and theoretical work is needed to further test the scenario and to understand the physics of the coevolution process - it is not obvious why the growth of dark-matter-dominated halos with total mass \( \sim 10^{12} \, M_\odot \) should have such a direct influence on the growth of central black holes with mass \( 10^6-8 \, M_\odot \). Meanwhile, other work in progress (Babić et al., these proceedings and in preparation) shows how both the AGN luminosity function and the X-ray background can be successfully reproduced within this framework, and it would be very interesting to extend this to higher redshifts.

A consequence of the predicted high Eddington ratios at high redshifts is that we expect a large fraction of galaxies to have nuclear outflows from their growing black holes (e.g. \cite{King2003, King&Pounds2003}) - searching for evidence of this would be important both for testing the hypothesis and for helping to understand the importance of feedback when galaxies formed.

Acknowledgments. I thank Y. Ueda for providing the data points used for the calculation shown in Fig. 1.

References

Barger, A.J., Cowie, L.L., Mushotzky, R.F., Yang, Y., Wang, W.-H., Steffen, A.T. & Capak, P. 2005, AJ, 129, 578
Barth, A.J., Greene, J.E. & Ho, L.C. 2005, ApJ, 619, L151
Beckert, T. & Duschl, W.J. 2002, A&A, 387, 422
Benson, A.J., Bower, R.G., Frenk, C.S., Lacey, C.G., Baugh, C.M. & Cole, S. 2003, ApJ, 599, 38
Blandford, R.D. & Znajek, R.L. 1977, MNRAS, 179, 433
Bower, R.G., Benson, A.J., Malbon, R., Helly, J.C., Frenk, C.S., Baugh, C.M., Cole, S. & Lacey, C.G. 2006, MNRAS, 370, 645
Boyle, B.J., Shanks, T. & Peterson, B.A. 1988, MNRAS, 235, 935
Boyle, B.J. & Terlevich, R.J. 1998, MNRAS, 293, L49
Cowie, L.L., Barger, A.J., Bautz, M.W., Brandt, W.N. & Garmire, G.P. 2003, ApJ, 584, L57
Croom, S.M., Boyle, B.J., Shanks, T. et al. 2005, MNRAS, 356, 415
Croton, D.J., Springel, V., White, S.D.M. et al. 2006, MNRAS, 365, 11
De Lucia, G., Springel, V., White, S.D.M., Croton, D. & Kauffmann, G. 2006, MNRAS, 366, 499
Di Matteo, T., Springel, V. & Hernquist, L. 2005, Nat, 433, 604
Dunlop J. 1997, ‘Observational Cosmology with the New Radio Surveys’, eds. Bremer et al., Kluwer
Fan, X. 2006, New Astronomy Reviews, 50, 665
Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9
Gebhardt, K., Bender, R., Bower, G. et al. 2000, ApJ, 539, 13
Goldschmidt, P. & Miller, L. 1998, MNRAS, 293, 107
Haehnelt M.G. & Rees M.J. 1993, MNRAS, 263, 168
Hasinger, G., Miyaji, T & Schmidt, M. 2005, A&A, 441, 417
Heckman, T., Kauffmann, G., Brinchmann, J. et al. 2004, ApJ, 613, 109
Ho, L. 2002, ApJ, 564, 120
Hewett, P.C., Foltz, C.B. & Chaffee, F.H. 1993, ApJ, 406, L43
Hopkins, P.F., Hernquist, L., Cox, T.J., Robertson, B., Di Matteo, T. & Springel, V. 2006, ApJ, 639, 700
Hopkins, P.F., Richards, G.T. & Hernquist, L. 2006, astro-ph/0605678
Kauffmann, G. & Haehnelt, M. 2000, MNRAS, 311, 576
King, A. 2003, ApJ, 596, 27
King, A. & Pounds, K.A. 2003, MNRAS, 345, 657
King, A. 2005, ApJ, 635, L121
Kollmeier, J.A., Onken, C.A., KocharSK, C.S. et al. 2006, ApJ, 648, 128
Lacy C. & Cole S. 1993, MNRAS, 262, 627
Lacy C. & Cole S. 1994, MNRAS, 271, 676
La Franca, F., Fiore, F., Comastri, A. et al. 2005, ApJ, 635, 864
Magorrian, J., Tremaine, S., Richstone, D. et al. 1998, AJ, 115, 2285
Marconi, A., RISALITI, G., Gilli, R. et al. 2004, MNRAS, 351, 169
Marshall, H.L., Tananbaum, H., Avni, Y. & Zamorani, G. 1983, ApJ, 269, 35
Miller, L. 1988, in NATO ASI series C, 229. Cooling Flows in Clusters and Galaxies, ed. A.C. Fabian (Dordrecht: Kluwer), 205 & 378
Miller, L., Percival, W.J., Croom, S.M. & Babić, A. 2006, A&A, in press, astro-ph/0608202
Narayan, R. & Yi, I. 1994, ApJ, 428, L13
Narayan, R. & Yi, I. 1995, ApJ, 452, 710
Netzer, H. & Trakhtenbrot, B. 2006, ApJ, in press, astro-ph/0607654
Onken, C.A., Ferrarese, L., Merritt, D. et al. 2004, ApJ, 615, 645
Pedlar, A., Ghataure, H., Davies, R.D., Harrison, B., Perley, R. & Crane, P.C. 1988, in NATO ASI series C, 229. Cooling Flows in Clusters and Galaxies, ed. A.C. Fabian (Dordrecht: Kluwer), 149 & 379
Pedlar, A., Ghataure, H.S., Davies, R.D., Harrison, B.A., Perley, R., Crane, P.C. & Unger, S.W. 1990, MNRAS, 246, 477
Percival, W.J. & Miller, L. 1999, MNRAS, 309, 823
Peterson, J.R. & Fabian, A.C. 2006, Physics Reports, 427, 1
Pounds, K.A., Reeves, J.N., King, A.R., Page, K.L., O’Brien, P.T. & Turner, M.J.L. 2003, MNRAS345, 705
Proga, D. & Kallman, T.R. 2004, ApJ, 616, 688
Reynolds, C. 2006, ApJ, in press, astro-ph/0607381
Richstone, D., Ajhar, E.A., Bender, R. et al. 1998, Nat, 395, A14
Steenbrugge, K.C., Kaastra, J.S., Crenshaw, D.M. et al. 2005, A&A, 434, 569
Steffen, A.T., Barger, A.J., Cowie, L.L., Mushotzky, R.F. & Yang, Y. 2003, AJ, 596, 23
Tremaine, S., Gebhardt, K., Bender, R. et al. 2002, ApJ, 574, 740
Trump, J.R., Hall, P.B., Reichard, T.A. et al. 2006, ApJS, 165, 1
Ueda, Y., Akiyama, M., Ohka, K. & Miyaji, T. 2003, ApJ, 598, 886
Zheng, W., Mikles, V.J., Mainieri, V. et al. 2004, ApJS, 155, 73