Co-Evolution of Central Black Holes and Galaxies

Keynote Address

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The Co-Evolution of Galaxies and Black Holes: Current Status and Future Prospects

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Abstract. I begin by summarizing the evidence that there is a close relationship between the evolution of galaxies and supermassive black holes. They evidently share a common fuel source, and feedback from the black hole may be needed to suppress over-cooling in massive galaxies. I then review what we know about the co-evolution of galaxies and black holes in the modern universe ($z < 1$). We now have a good documentation of which black holes are growing (the lower mass ones), where they are growing (in the less massive early-type galaxies), and how this growth is related in a statistical sense to star formation in the central region of the galaxy. The opportunity in the next decade will be to use the new observatories to undertake ambitious programs of 3-D imaging spectroscopy of the stars and gas in order to understand the actual astrophysical processes that produce the demographics we observe. At high redshift ($z > 2$), the most massive black holes and the progenitors of the most massive galaxies are forming. Here, we currently have a tantalizing but fragmented view of their co-evolution. In the next decade, the huge increase in sensitivity and discovery power of our observatories will enable us to analyze the large, complete samples we need to achieve robust and clear results.

1. Introduction

We live in very interesting times today. On the one hand, we have precision measurements of the geometry, age, composition, and density-fluctuation power spectrum of the universe (Spergel *et al.* 2007). The predictions of inflationary cosmology and the ΛCDM paradigm have been confirmed, so that we also have a robust understanding of the development and evolution of the structure of the dark-matter backbone of the universe (e.g., Tegmark *et al.* 2004). This might suggest that our work is largely done. Paradoxically however, it is that minority component of the mass-energy content of the universe with which we have the most experience by far – ordinary baryonic matter – whose cosmic evolution has proven to be most difficult to understand. Ordinary matter can interact dissipatively, radiate, cool, respond to pressure gradients, generate and respond to magnetic fields, undergo nuclear reactions, etc. This richness of physical processes leads directly to a corresponding richness of astrophysical phenomena that have inspired and challenged astronomers for centuries.

So, with the basic cosmological framework firmly in place, the challenge in the study of the formation and evolution of galaxies is to understand the complex gastro-physics of the gas-star-black hole cosmic ecosystem. The role of supermassive black holes is particularly mysterious. At least out to a redshift of three, the overall evolution in the rates of star-formation and black hole accretion track one another rather well: a steep rise by about an order-of-magnitude from $z = 0$ to 1 and then relatively little change between $z = 1$ to 3 (e.g., Marconi *et al.* 2004). Coupled with the tight correlation between the mass of the black hole and the velocity dispersion and mass of the galactic bulge within which it resides (e.g., Gultekin *et al.* 2009; Marconi & Hunt 2003; Haring & Rix 2004), there is then compelling evidence for a close connection between the formation of the black hole and that of its host galaxy (e.g., Kauffmann & Haehnelt 2000; Granato *et al.* 2001).

This close connection would seemingly require a two-way communication between the black hole and its host galaxy, and this then poses a number of questions for which there are no firm answers: How are supermassive black holes fed? How is the growth of the supermassive black hole regulated? Do supermassive black holes significantly affect the formation/evolution of their host galaxy (and if so, how)?

This last question is the one that has drawn the most attention over the past several years because it bears directly on a major problem with current models of the formation of massive galaxies. These models predict that massive galaxies should in general be surrounded by a substantial reservoir of gas which should be cooling and forming stars. Over a Hubble time, these processes should have produced far more present-day galaxies with large stellar masses than are actually observed. Similarly, the cooling rate of hot gas in the haloes of massive galaxies today should be high enough to produce an easily-observable population of young stars (e.g., Kauffmann, White, & Guiderdoni 1993). A great deal of theoretical and observational effort is now being expended on understanding why this simple expectation does not appear to be borne out by observations. Matter accreting onto central supermassive black holes can, in principle, provide a vast source of energy, and jets or outflows can provide mechanisms for transporting the energy to large enough radii to regulate cooling and star formation in the massive galaxies where such black holes live (e.g., Churazov *et al.* 2001; Croton *et al.* 2006; Bower *et al.* 2006; Hopkins *et al.* 2008; Di Matteo *et al.* 2008).

My plan for the rest of this review is as follows. I will begin on the firmest ground by discussing the modern universe ($z < 1$). We know quite a lot already about the overall landscape, but not much about the actual astrophysical processes that connect the fueling of the black hole to star formation in the galaxy bulge. Then I will discuss the early universe ($z > 2$), the epoch when the most massive black holes and galaxies were forming. There have been remarkable developments over the past few years, but the picture is still fragmented.

2. The Modern Universe: What Do We Know Now?

2.1. *An Overview*

In the present-day universe, there are two nearly independent modes of black hole activity. The first is associated with Seyfert galaxies and QSOs. Here, the black hole is radiating strongly (typically at greater than a few percent of the Eddington limit). The second mode (radio galaxies) is dominated by the most massive black holes living in the most massive galaxies (giant ellipticals). Here, the accretion rates are low and the accretion process is radiatively inefficient. Instead, energy is being extracted from the black hole in the form of highly collimated relativistic jets that produce nonthermal radio emission.

2.2. *Seyfert Galaxies and QSOs: The Population of Rapidly Growing Black Holes*

The relatively rapid growth of black holes that takes place in Seyfert nuclei and QSOs is accompanied by strong emission from the accretion disk and its environment In principle, this emission can swamp that of the host galaxy, making it difficult to determine the properties of the host galaxy and relate these to the growth of the black hole. Fortunately, nature has provided us with its own coronagraph. The central black hole and its accretion disk are encircled by a dusty torus that is opaque to the ultraviolet and optical emission from the accretion disk (Krolik & Begelman 1988). When viewed from near the equatorial plane of the torus, the accretion disk cannot be seen directly and the object is called a

Type 2 Seyfert galaxy (or Type 2 QSO, if sufficiently luminous). In the Type 2 Seyferts, the observed ultraviolet through near-infrared continuum is dominated by the host galaxy (e.g., Kauffmann *et al.* 2003c). The presence of the obscured AGN can be recognized by the strong mid-infrared emission from the dusty torus, by the high-ionization narrow UV, optical, and IR emission-lines produced as the ionizing radiation from the accretion disk escapes along the polar axis of the torus and photoionizes gas in the surrounding kpc-scale narrow-line region (NLR), and by hard X-rays that have passed directly through the torus (if the torus is Compton-thin).

Our largest sample of local ($z \sim 0.1$) Type 2 AGN and their host galaxies has come from the Sloan Digital Sky Survey (SDSS). These AGN were recognized by the emission of the NLR in the SDSS spectra (Kauffmann *et al.* 2003c; Hao *et al.* 2005). The AGN luminosity can be estimated from the strong [O III] λ5007 emission line and an empirically derived bolometric correction (Heckman *et al.* 2004), while the black hole mass can be determined from the bulge velocity dispersion σ and the $M_{\rm BH}$–σ relation (Tremaine *et al.* 2002). The SDSS spectra plus multicolor optical images and *GALEX* near- and far-ultraviolet images can be used to determine the fundamental properties of the host galaxies (star-formation rate, stellar mass, velocity dispersion, structure, and morphology) and of the local clustering environment (Kauffmann *et al.* 2003a, 2004,2007; Brinchmann *et al.* 2004; Li *et al.* 2008; Wild *et al.* 2007; Reichard *et al.* 2008; Martin *et al.* 2007).

The first question we can ask is: Which black holes are growing? The SDSS sample of Type 2 AGN shows that most present-day accretion occurs onto lower-mass black holes ($< 10^8\ M_\odot$). In fact, the volume-averaged accretion rates of low-mass black holes imply that this population is currently growing (doubling its mass) on a timescale that is comparable to the age of the universe (Heckman *et al.* 2004). In contrast, the mass-doubling timescale is more than two orders of magnitude longer for the population of the most massive black holes ($> 10^9\ M_\odot$). These dormant black holes evidently formed at early times, and once blazed as powerful QSOs.

The next question we can ask is: In which galaxies are black holes currently growing? It is now well-known that the present-day galaxy population consists of two families (e.g., Kauffmann *et al.* 2003b; Baldry *et al* 2004; Brinchmann *et al.* 2004; Schiminovich *et al.* 2007). One family is lower in mass, disk-dominated, rich in cold gas, and experiencing significant rates of star-formation. The other family is higher in mass, bulge-dominated, depleted in cold gas, and experiencing little if any star formation.

It is very intriguing that a majority of galaxies that lie in no-man's land between these two galaxy populations host AGN (Martin *et al.* 2007; Kauffmann *et al.* 2007). There are also systematic trends in host properties with AGN luminosity (Cid Fernandes *et al.* 2001; Kauffmann *et al.* 2003c; Kauffmann *et al.* 2007; Wild *et al.* 2007). The higher the luminosity of the AGN, the younger is the age of the stellar population in the central-most few kpc, the higher is the likelihood that the galaxy has experienced a burst of star formation within the last gigayear, and the greater is the amount of dust extinction towards the bulge (a proxy for the presence of cold gas). These results at $z \sim 0.1$ are at least qualitatively consistent with what is known about AGN host galaxies at $z \sim 0.5$ to 1 (Nandra *et al.* 2007; Rovilos *et al.* 2007; Rovilos & Georgakakis 2007; Hickox *et al.* 2009; Silverman *et al.* 2009; Zakamska *et al.* 2006; Liu *et al.* 2009).

The relationship between star-formation and black hole growth strongly suggests a common fuel source: cold dense gas. But by what mechanism is this gas transported inward towards the black hole? In most of the popular models for the co-evolution of black holes and galaxies, the dominant phase of black hole growth occurs in the aftermath of a major merger between two gas-rich disk galaxies (e.g., Di Matteo *et al.* 2008; Hopkins *et al.* 2008). This growth coincides with or closely follows a central burst of star-formation.

However, at least in the modern universe ($z < 1$), a strong connection between major mergers and black hole growth has not been established. In particular, Reichard *et al.* (2008) measured the lopsidedness of the stellar distribution in the host galaxies of low-redshift Type 2 AGN in the SDSS. They found that the more rapidly growing black holes do not live in galaxies that are more lopsided than normal galaxies with the same mass and stellar population. Similarly, Li *et al.* (2008), found no evidence for an excess of close companion galaxies near Type 2 AGN in the SDSS. These results agree with a number of investigations of the host galaxies of AGN at $z \sim 1$ (Grogin *et al.* 2005; Pierce *et al.* 2007; Gabor *et al.* 2009).

There is mounting evidence that the source of gas that is accreted by the black hole in typical local AGN is mass-loss from evolved intermediate mass stars. Kauffmann & Heckman (2009) find that the demographics of the population of black holes in bulges with little on-going star formation can be explained if the black holes captures 0.3 to 1% of the stellar mass loss in the bulge. Wild *et al.* (2010) find that the time dependence of black hole growth following a strong starburst is consistent with the accretion of 0.5% of the stellar mass lost during the post-supernova phase of the aging starburst. This idea was first proposed by Norman & Scoville (1988), and the accreted fractions are in good agreement with theoretical predictions by Ciotti & Ostriker (2007).

As noted in the introduction, feedback from the AGN is believed to be an important process in the evolution of massive galaxies. Some of the most successful models assume that a significant amount of the rest-mass energy of the matter accreted by the black hole is available to drive a powerful galactic wind (e.g., Hopkins *et al.* 2008; Di Matteo *et al.* 2008). To date, there is little strong evidence in the local universe that such processes operate on galactic scales in typical Seyfert galaxies, although some spectacular outflows (likely to have been launched by a previous AGN outburst) have been observed in massive post-starburst systems at intermediate redshifts (Tremonti *et al.* 2007).

It is also important here to emphasize that since there is strong link between the growth of black holes and star formation. Feedback in the form of the kinetic energy supplied by supernovae and stellar winds from massive stars will be available even if the black hole does not help at all. As an illustration, the formation of a $10^8\ M_\odot$ black hole would be (eventually) accompanied by the formation of $\sim 10^{11}\ M_\odot$ in stars, resulting in $\sim 10^9$ supernovae and $\sim 10^{60}$ ergs in kinetic energy. This is equivalent to $\sim$1% of the rest-mass energy of the black hole, and is sufficient (in principle) to expel the entire ISM of such a galaxy. This feedback may play a major role in regulating the growth of the black hole (Davies *et al.* 2007, 2009b; Wild *et al.* 2010).

2.3. *Radio Galaxies: Homes of the Most Massive Black Holes*

Unlike the case of the Seyfert galaxies and QSOs, typical radio galaxies in the present-day universe appear to be accreting at a highly sub-Eddington rate, and in a radiatively inefficient mode (e.g., Allen *et al.* 2006). Most of the energy extracted from the black hole appears in the form of highly collimated relativistic outflows of radio-emitting plasma.

A cross-match of the SDSS main galaxy sample and the FIRST and NVSS radio catalogs yields a sample of several thousand local ($z \sim 0.1$) radio galaxies (Best *et al.* 2005a). This sample is dominated by relatively low-power radio sources (the so-called FR-I sources). Best *et al.* (2005b) and Kauffmann *et al.* (2008) showed that this class of AGN is almost totally disjoint from the Seyfert/QSO population described above. The properties of the radio galaxies differ in several strong and systematic ways from the Type 2 Seyfert galaxies described in the preceding section. The radio galaxies are selectively drawn from the population of the most massive galaxies (quantifying the well-known result that they are typically giant elliptical galaxies). They also showed that these

FR-I radio galaxies had the old stellar populations and highly concentrated structures of normal giant elliptical galaxies. Similar results have been found at $z \sim 1$ (Gabor *et al.* 2009).

The strong mass dependence of the radio luminosity function can be understood as reflecting the mass dependence of the cooling rate of hot gas in elliptical galaxies (Best *et al.* 2005b). In fact, *Chandra* high-resolution X-ray imaging spectroscopy of the hot gas in the centers of the nearest such radio galaxies shows that the radio jet power scales directly with the estimated rate of Bondi accretion in these systems (Allen *et al.* 2006). Further support for this fueling scenario comes from the enhanced probability of radio emission from the brightest galaxies at the centers of groups and clusters of galaxies – just the locations where the cooling rates will be unusually high (Best *et al.* 2007).

There is now quite compelling evidence for feedback provided by radio sources. The most direct evidence comes from observations of the cavities evacuated in the hot gas in the cores of galaxy clusters by radio sources (e.g., Fabian *et al.* 2006; Birzan *et al.* 2004; McNamara & Nulsen 2007). The sizes of the cavities and the measured gas pressure allows the amount of $P\Delta V$ work done by the radio source to be calculated, while the sound-crossing time of the cavity gives a characteristic time scale. This then allows a rough estimate to be made of the time-averaged rate of energy transported by the radio jets. Best *et al.* (2006) used this approach to derive the scaling between the observed radio luminosity of the jet and its rate of energy transport. Combining this scaling relation with the mass-dependent radio luminosity function of Best *et al.* (2005b), they were able to show that the time-averaged mass-dependent heating rate due to radio jets roughly matches the measured average mass-dependent radiative cooling rates (X-ray luminosities) in elliptical galaxies.

Work by Sadler *et al.* (2007) and Donoso *et al.* (2009) shows that the co-moving density of FR-I radio galaxies roughly doubles between $z \sim 0$ and 0.7. The associated heating rate per co-moving volume would likewise have been larger then, while the total amount of stellar mass in elliptical galaxies was smaller (Bell *et al.* 2004; Faber *et al.* 2007). Thus, this form of feedback would have more important (more ergs per gram) than at present.

3. The Modern Universe: Prospects for the Next Decade

From the summary above, it appears that we have a pretty clear overall map of the basic landscape in the local universe: we know which black holes are growing and in what kinds of galaxies. Having said that, it is also clear that we have a very incomplete understanding of the actual astrophysical processes at work. In what follows, I will highlight a few issues where I think the combination of major new facilities will allow us to make dramatic discoveries in the next decade.

3.1. *The Importance of Surveys*

At a redshift of one, the global rates of both star formation and black hole growth were about an order of magnitude larger than today (e.g., Marconi *et al.* 2004). This is very intriguing because (from what we have seen so far) the universe at $z \sim 1$ does not look radically different from that at $z \sim 0$. The familiar galaxies that define the Hubble sequence are in place, and the scaling relations and building blocks that define the basic structures of galaxies have not evolved strongly (e.g., Barden *et al.* 2005; Jogee *et al.* 2004). As summarized above, the growth of black holes seems to occur in galaxies that are at least qualitatively similar to those in which black holes grow today. The relationship between black hole mass and galaxy velocity dispersion has apparently evolved only weakly if at all (Salviander *et al.* 2007, but see Woo *et al.* 2007). So the $z \sim 1$ universe

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looks sort of like the $z \sim 0$ universe on steroids. The most important difference presumably is the higher overall amount of cold gas in (and/or accretion rate onto) galaxies at $z \sim 1$.

A major new wide field multi-object optical/near-IR spectrograph on an 8 or 10 meter-class telescopes would make it be feasible in the next decade to undertake the rough equivalent of the SDSS at $z \sim 1$.

3.2. *Fueling the Black Hole*

We now know that there is a strong link (at least in a statistical sense) between star formation in the innermost several kpc and the growth of black holes. Perhaps the most important unanswered question about AGN is how some small fraction of the cold gas supply being used to form stars is transported over many orders of magnitude in radius to the accretion disk around the black hole. This process must be directly related to the mysteriously constant ratio of $\sim 10^3$ between the masses the bulge and its black hole. Tackling this problem well requiries a program of high angular resolution imaging spectroscopy of complete samples of nearby AGN.

The most exciting prospect would be to probe the regime where the gravitional potential of the black hole itself starts to dominate the dynamics. This critical radius is $\sim 12(M_{\rm BH}/10^8\, M_\odot)^{1/2}$ parsecs. For the nearest AGN, this correponds to an angular scale of about $0\farcs1$. With *JWST* and an AO-fed GSMT/E-ELT, we will just be able access this regime and map the emission of hot dust (Tristram *et al.* 2007) and hot molecular hydrogen (Davies *et al.* 2006; Hicks & Malkan 2008). On larger spatial scales, *JWST*, GSMT/E-ELT, and ALMA could be used to map out the distribution and kinematics of ionized and molecular gas for a large and complete sample of AGN and suitable control sample (e.g., Fathi *et al.* 2006; Storchi-Bergmann *et al.* 2007; Riffel *et al.* 2008; Davies *et al.* 2009a; Lindt-Krieg *et al.* 2008; Schinnerer *et al.* 2000). A complementary approach could be provided by mapping of the stellar population and star-formation history in these regions (e.g., Gonzalez Delgado *et al.* 2004; Davies *et al.* 2007).

3.3. *Tracing Feedback*

The powerful capabilities for X-ray spectroscopy provided by the proposed *International X-ray Observatory (IXO)* will give us revolutionary insights into AGN-driven feedback. With an imaging X-ray calorimeter it will be possible for the first time to actually make spatially resolved maps of the detailed kinematics of the hot gas that is being accelerated and heated by radio sources in clusters and giant elliptical galaxies. Complementary studies using 3-D spectroscopy with high angular resolution (*JWST*, AO-fed GSMT/E-ELT) can investigate the affects of AGN feedback on warm ionized gas.

A combination of high spectral resolution and sensitivity in the X-ray and rest-frame far-UV will also make it possible to conduct a major campaign of time-domain studies of the AGN-driven outflows traced through their blue-shifted absorption lines. Such studies are the best way to determine the size-scales of these outflows, and hence the outflow rates of mass and energy carried by them.

4. The Early Universe

4.1. *Overview*

In summarizing above what we know about the modern universe, I emphasized results from large, homogeneously selected, and complete samples. I also emphasized the importance of spectroscopy. Such an approach has allowed us to decisively resolve some long-standing controversies, quantify long-known or long-suspected qualitative results,

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and discover the unexpected. Unfortunately, at high-redshift this approach is essentially impossible with our current capabilities.

It is obvious that at high redshift the host galaxies of AGN are faint, and so it is not currently possible to observe very large samples. A less obvious but equally important problem is that it is very difficult with the present data to robustly characterize the basic properties of both the AGN (e.g., bolometric luminosity, black hole mass, Eddington ratio) and those of its host galaxy (e.g., stellar mass, star formation rate, velocity dispersion, structure/morphology). We have a reasonable handle on the AGN properties in high-z QSOs, but then have very limited information about their host galaxies. As at low redshift, it is easier to study the properties of the host galaxies in Type 2 AGN. The main techniques for finding Type 2 AGN at high redshift are through observations in the rest-frame mid-IR or in the hard X-ray band, supplemented by radio continuum observations. Unfortunately, with only this limited coverage of the full spectral energy distribution, it is often difficult to cleanly separate out AGN from powerful starbursts.

Here is one way of thinking about the problem. We know that star formation and black hole growth are coupled, and that in a time-averaged sense the ratio of these two rates is of order 10^3 (e.g., Marconi *et al.* 2004). Models suggest that this ratio is more like 10^2 during the phase when the black hole growth rate is maximized (e.g., Hopkins *et al.* 2008). The ratio of bolometric luminosity (stars/black hole) corresponding to the two ratios above are $\sim$10 and $\sim$1, respectively (assuming a radiative efficiency of 10% for black hole accretion and assuming a Kroupa IMF for the star formation). Thus, we expect both phenomena to be energetically significant in high-redshift AGN. Sorting out the luminosity attributable to the AGN (measuring the black hole accretion rate) and to the young stars (determining the star-formation rate) is not straightforward with the limited available data. Even assuming we can determine the AGN bolometric luminosity, we usually have only a lower limit to the black hole mass in Type 2 AGN (by assuming that the Eddington limit is obeyed).

4.2. *Which Came First?*

The tight relationship at $z \sim 0$ between the mass of the black hole and the mass and velocity dispersion of the galaxy bulge within which it lives is the result of a time integral over the history of the universe. It does not however tell us that the two formation processes must occur simultaneously in any given galaxy. If not, which comes first: the black hole or the galaxy?

There have been a number of attempts to determine the relationship between the galaxy mass (or velocity dispersion) and black hole mass at high redshift. Unfortunately, these different studies have not come to consistent conclusions. Some (e.g., Peng *et al.* 2006; McLure *et al.* 2006) find that the ratio of black hole to galaxy mass is several times larger at high redshift (i.e., the black hole comes first). Others (e.g., Shields *et al.* 2003; Jahnke *et al.* 2009) found no evidence that the relation between black hole mass and galaxy mass and/or velocity dispersion had evolved strongly between $z \sim 0$ to $z \sim 2$–3. Borys *et al.* (2005) point out that if the black holes detected in sub-mm galaxies via their hard X-ray emission are accreting at the Eddington rate, their luminosites would imply that they have masses more than an order of magnitude below that of black holes today in galaxies with similar mass (e.g., the galaxy would come before the black hole).

Hopkins *et al.* (2006) use integral constraints on the co-moving mass density of black holes to argue that there cannot be a strong evolution in the ratio of stellar and black hole mass in galaxies. Small changes will be difficult to detect, especially when the ferocious systematic effects discussed by Lauer *et al.* (2007) are considered. Lauer *et al.* argue that a robust attack on this problem requires both an accurate measurement of the scatter-function in the $M_{\rm BH}$ versus $M_{\rm Gal}$ or versus σ relations, and samples at high and low redshift that have been selected (and investigated) in exactly the same way using precisely defined and objective criteria. This task will be far easier using the capabilities of *JWST*, GSMT, and E-ELT to characterize the salient properties of large samples of galaxies at high redshift.

4.3. *How Are Black Holes Fueled?*

At low redshift, AGN activity seems to be triggered by both the inflow of relatively cold gas in medium-mass systems (the Seyfert galaxies) and of hot gas in the most massive galaxies (the radio galaxies). Models imply that the relative importance of the cold mode will increase at high redshifts and dominate in both the low and high mass galaxies (e.g., Keres *et al.* 2005; Croton *et al.* 2006). In such models, cold accretion can occur episodically, and many models link the formation of black holes to major merger events (e.g., Hopkins *et al.* 2008; Di Matteo *et al.* 2008). Can we see clear evidence at high-z that the growth of black holes is indeed driven by mergers or major accretion events?

Imaging the host galaxies of high-z QSOs is very challenging, even with *HST*. The investigations to date (Ridgway *et al.* 2001; Kukula *et al* 2001; Peng *et al.* 2006) have determined only the most basic properties (luminosity and size) of the host galaxies for relatively small samples. The images are not sensitive enough to detect large-scale low-surface brightness tidal features while the inner regions are strongly contaminated by the QSO.

In the absence of a bright central QSO, it is easier to look for morphological evidence for mergers in Type 2 AGN. Imaging of high-redshift FR-II radio galaxies do show spectacular examples of what appear to be the coalescence of a massive galaxy (e.g., Miley *et al.* 2006), but these are exceedingly rare systems compared to typical high-z AGN. Based on *HST* imaging, Pope *et al.* (2005) and Chapman *et al.* (2003) conclude that high-z sub-mm galaxies (shown by X-ray observations to contain growing black holes) are larger and more asymmetric than other galaxies at these redshifts, and have the complex irregular morphologies suggestive of mergers.

Progress in the next decade will come through two complementary approaches. First, the high angular resolution, stable point spread function, and superb sensitivity of NIR-CAM on *JWST* will enable us to accurately characterized the morphologies of large samples of the host galaxies of high-redshift AGN, including QSOs. This will allow us to quantify the incidence rates of recent mergers in these objects. We may be able to learn about the relative sequencing of the star formation and black hole growth by comparing samples of systems that appear to be in the early versus late stage of the merger. Second, high spatial resolution 3-D imaging spectroscopy on *JWST*, GSMT, and E-ELT will make it possible to map the ionized gas in the AGN host galaxies, while ALMA will do the same for the molecular gas. These data could provide direct kinematic evidence that we are witnessing the aftermath of a major accretion/merging event and would pinpoint the location and kinematics of the molecular gas that is fueling the star-formation traced by the ionized gas. Programs with the current generation of facilities give us tantalizing examples of the power of such an approach (e.g., Forster Schreiber *et al.* 2006; Bouche *et al.* 2007; Nesvadba *et al.* 2008a; Law *et al.* 2007).

4.4. *AGN Feedback*

The co-moving rate of accretion onto black holes at $z \sim 2$ to 3 was about a factor of $\sim$30 higher than today. Feedback related to this black hole building could have a dramatic effect on the formation and evolution of massive galaxies. Do we see it in action? Here

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the situation is somewhat similar to what we see in the modern universe: the most direct and convincing evidence of feedback that is being driven by the AGN and is having a dramatic impact on gas on galactic scales is found in the form of radio jets.

The presence of galaxy-scale emission-line nebulae around radio-loud QSOs and powerful FR-II radio galaxies at high-z has long been known (e.g., McCarthy *et al.* 1996; Heckman *et al.* 1991a,b). Long-slit spectroscopy of these systems shows the presence of high gas velocities (of order 10^3 km s^{-1}), strongly suggesting the outflow of substantial amounts of gas. The morphological connection between the ionized gas and the radio sources supports the idea that the outflow is driven by the radio source itself (not by radiation pressure or a spherical wind blown by the black hole). This is consistent with the much smaller, fainter, and more quiescent emission-line nebulae seen around radio-quiet QSOs at the same high redshifts (Christensen *et al.* 2006; Nesvadba, private communication).

Recently, very detailed maps in the rest-frame optical have been made for several of the high-z FR-II radio galaxies (Nesvadba *et al.* 2006, 2008b) using near-IR IFU spectroscopy. These data provide for the first time detailed maps of the kinematics and and physical conditions in the regions, and provide convincing confirmation of the idea that the radio sources are likely to be blasting away the entire gaseous halo around the galaxy. This is very exciting, but we must keep in mind that black holes with radio sources this powerful constitute only a small minority ($\sim$0.1%) of the rapidly growing supermassive black holes at these redshifts.

With the enormous increase in capability for imaging spectroscopy provided by *JWST*, GSMT, and E-ELT, it would be relatively easy to undertake detailed investigations like this of large and complete samples of all the important classes of AGN at high redshift. The capabilities for high resolution X-ray spectroscopy provided by *IXO* can be used to investigate the physics of AGN feedback traced by the hot gas. Finally, with GSMT/E-ELT it will possible to obtain spectra of background galaxies seen along site lines that pass through the halos of high-z AGN host galaxies. This would allow us to probe the effects of feedback on the gaseous halo of the AGN host galaxy through the measurements of the associated UV absorption lines (Steidel *et al.* 2010).

5. Final Thoughts

I began this paper by listing all the unanswered questions we have about how the co-evolution of black holes and galaxies actually works. How does gas get into galaxies in the first place? Once inside, how is it transported all the way to the black hole accretion disk? What astrophysics sets the mass ratio of the gas turned into stars compared to the gas accreted by the black hole (why is this ratio $\sim 10^3$)? What is the real astrophysics of the feedback from the supermassive black hole that seems to be a crucial ingredient in galaxy evolution? What is the sequencing, both in the sense of overall cosmic history and in the life of an individual galaxy? Does the black hole or galaxy form first? Is the rapid growth of a black hole a once-in-a-lifetime transformative event in the life of a galaxy (e.g., a major merger followed by catastrophic feedback), or is it a more gradual, intermittent process? Does the answer depend on redshift and/or black hole mass?

I have tried to describe our current state of knowledge and ignorance, and have also tried to summarize how I think we can use the amazing new observatories of the next decade to best answer these questions. Given that we are trying to understand a complex cosmic eco-system consisting of hot gas, cold dusty gas, stars, and black holes, it seems clear to me that a panchromatic approach is essential. *JWST*, ALMA, GSMT/E-ELT, and *IXO* will all play crucial roles. I have also tried to emphasize the importance of spectroscopy and of 3-D imaging-spectroscopy in particular. Again, the capabilities of these observatories are a superb match to the problem at hand. Finally, I have emphasized the importance of large surveys of complete and carefully selected samples. The increase in raw sensitivity provided by the new observatories will help make this approach feasible. The huge gain in discovery power provided by of a new generation of multi-object optical and near-IR spectrographs on existing 8 and 10-meter class telescopes would allow us to undertake SDSS-scale surveys at redshifts of one and beyond.

References

Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, *MNRAS*, 372, 21

Baldry, I. K., Glazebrook, K., Brinkman, J., Ivezic, Z., Lupton, R., Nichol, R., & Szalay, A. 2004, *ApJ*, 600, 681

Barden, M., *et al.* 2005, *ApJ*, 635, 959

Bell, E. F., Wolf, C., Meisenheimer, K., Rix, H.-W., Borch, A., Dye, S., Kleinheinrich, M., Wisotzki, L., & McIntosh, D. H. 2004, *ApJ*, 608, 752

Best, P. N., Kauffmann, G., Heckman, T. M., & Ivezic, Z. 2005a, *MNRAS*, 362, 9

Best, P. N., Kauffmann, G., Heckman, T. M., Brinchmann, J., Charlot, S., Ivezic, Z., & White, S. D. M. 2005b, *MNRAS*, 362, 52

Best, P. N., Kaiser, C. R., Heckman, T. M., & Kauffmann, G. 2006, *MNRAS*, 368, L67

Best, P. N., von der Linden, A., Kauffmann, G., Heckman, T. M., & Kaiser, C. R. 2007, *MNRAS*, 379, 894

Brzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, *ApJ*, 607, 800

Borys, C., Smail, I., Chapman, S. C., Blain, A. W., Alexander, D. M., & Ivison, R. J. 2005, *ApJ*, 635, 853

Bouche, N., *et al.* 2007, *ApJ*, 671, 303

Bower, R., Benson, A., Malbon, R., Helly, J., Frenk, C., Baugh, C., & Lacey, C. 2006, *MNRAS*, 370, 645

Brinchmann, J., Charlot, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., & Brinkmann, J. 2004, *MNRAS*, 351, 1151

Chambers, K. C., Miley, G. K., van Breugel, W. J. M., Bremer, M. A. R., Huang, J.-S., & Trentham, N. A. 1996, *ApJS*, 106, 247

Ciotti, L. & Ostriker, J. 2007, *ApJ*, 665, 1038

Chapman, S. C., Windhorst, R., Odewahn, S., Yan, H., & Conselice, C. 2003, *ApJ*, 599, 92

Christensen, L., Jahnke, K., Wisotzki, L., & Sanchez, S.F. 2006, *A&A*, 459, 717

Churazov, E., Brggen, M., Kaiser, C. R., Bhringer, H., & Forman, W. 2001, *ApJ*, 554, 261

Cid Fernandes, R., Heckman, T., Schmitt, H., Delgado González, R., & Storchi-Bergmann, T. 2001, *ApJ*, 558, 81

Croton, D. J., Springel, V., White, S. D. M., De Lucia, G., Frenk, C. S., Gao, L., Jenkins, A., Kauffmann, G., Navarro, J. F., & Yoshida, N. 2006, *MNRAS*, 365, 11

Davies, R. I., Thomas, J., Genzel, R., Mueller Sanchez, F., Tacconi, L., Sternberg, A., Eisenhauer, F., Abuter, R., Saglia, R. & Bender, R. 2006, *ApJ*, 646, 754

Davies, R. I., Mueller Sanchez, F., Genzel, R., Tacconi, L. J., Hicks, E. K. S., Friedrich, S., & Sternberg, A. 2007 *ApJ*, 671, 1388

Davies, R. I., Maciejewski, W., Hicks, E., Tacconi, L., Genzel, R., & Engel, H. 2009a, *ApJ*, 702, 114

Davies, R. I., Hicks, E., Schartmann, M., Genzel, R., Tacconi, L., Engel, H., Burkert, A., Krause, M., Sternberg, A., Mueller Sanchez, F., & Maciejewskji, W., 2009b [arXiv:0911.4355]

Donoso, E., Best, P., & Kauffmann, G. 2009, *MNRAS*, 392, 617

Di Matteo, T., Colberg, J., Springel, V., Hernquist, L., & Sijacki, D. 2008, *ApJ*, 676, 33

Faber, S., *et al.* 2007, *ApJ*, 665, 265

Fabian, A., Sanders, J., Taylor, G., Allen, S., Crawford, C., Johnstone, R., & Iwasawa, K. 2006, *MNRAS*, 366, 417

Fathi, K., Storchi-Bergmann, T., Riffel, R. A., Winge, C., Axon, D. J., Robinson, A., Capetti, A., & Marconi, A. 2006, *ApJ*, 641, L25

Forster Schreiber, N., *et al.* 2006, *AJ*, 131 1891

Gabor, J. M., *et al.* 2009, *ApJ*, 691, 705

González Delgado, R., Cid Fernandes, R. Perez, E., Martins, L. P. Storchi-Bergmann, T., Schmitt, H., Heckman, T., & Leitherer, C. 2004, *ApJ*, 605, 127

Granato, G. L., Silva, L., Monaco, P., Panuzzo, P., Salucci, P., De Zotti, G., & Danese, L. 2001, *MNRAS*, 324, 757

Grogin, N. A., *et al.* 2005, *ApJ*, 627, L97

Gultekin, K., *et al.* 2009, *ApJ*, 698, 198

Hao, L., *et al.* 2005, *AJ*, 129, 1783

Haring, N. & Rix, H.-W. 2004, *ApJ*, 604, L89

Heckman, T. M., Miley, G. K., Lehnert, M. D., & van Breugel, W. 1991a, *ApJ*, 370, 78

Heckman, T. M., Lehnert, M. D., Miley, G. K., & van Breugel, W. 1991b, *ApJ*, 381, 373

Heckman, T., Kauffmann, G., Brinchmann, J., Charlot, S., Tremonti, C., & White, S. 2004, *ApJ*, 613, 109

Hickox, R., *et al.* 2009, *ApJ*, 696, 891

Hicks, E. & Malkan, M. 2008, *ApJS*, 174, 31

Hopkins, P. F., Robertson, B., Krause, E., Hernquist, L., & Cox, T. J. 2006, *ApJ*, 652, 107

Hopkins, P. F., Hernquist, L., Cox, T. J., & Keres, D. 2008, *ApJS*, 175, 356

Jahnke, K., *et al.* 2009, *ApJ*, 706, L215

Jogee, S., *et al.* 2004, *ApJ*, 615, L105

Kauffmann, G. & Haehnelt, M. 2000, *MNRAS*, 311, 576

Kauffmann, G., White, S. D. M, & Guiderdoni, B. 1993, *MNRAS*, 264, 201

Kauffmann, G., *et al* 2003a, *MNRAS*, 341, 33

Kauffmann, G., Heckman, T. M., White, S. D. M., Charlot, S., Tremonti, C., Peng, E. W., Seibert, M., Brinkmann, J., Nichol, R. C., SubbaRao, M., & York, D. 2003b, *MNRAS*, 341, 54

Kauffmann, G., *et al.* 2003c, *MNRAS*, 346, 1055

Kauffmann, G., White, S. D. M., Heckman, T. M. Menard, B., Brinchmann, J., Charlot, S., Tremonti, C.. & Brinkmann, J. 2004, *MNRAS*, 353, 713

Kauffmann, G., *et al.* 2007, *ApJS*, 173, 357

Kauffmann, G., Heckman, T., & Best, P. 2008, *MNRAS*, 384, 953

Kauffmann, G. & Heckman, T. 2009, *MNRAS*, 397, 135

Keres, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, *MNRAS*, 363, 2

Krolik, J. H. & Begelman, M. 1988, *ApJ*, 329, 702

Kukula, M. J., Dunlop, J. S., McLure, R. J., Miller, L., Percival, W. J., Baum, S. A., & O'Dea, C. P. 2001, *MNRAS*, 326, 1533

Lauer, T. R., Tremaine, S., Richstone, D., & Faber, S. M. 2007, *ApJ*, 670, 249

Law, D. R., Steidel, C. C., Erb, D. K., Larkin, J., Pettini, M., Shapley, A., & Wright, S. A. 2007, *ApJ*, 669, 929

Li, C., Kauffmann, G., Heckman, T. M., White, S. D. M., & Jing, Y. P. 2008, *MNRAS*, 385, 1915

Lindt-Krieg, E., Eckart, A., Neri, R. Krips, M., Pott, J.-U., Garcia-Burillo, S., & Combes, F. 2008, *A&A*, 479, 377

Liu, X., Zakamska, N., Greene, J., Strauss, M., Krolik, J., & Heckman, T. 2009, *ApJ*, 702, 1098

Marconi, A. & Hunt, L. K. 2003, *ApJ*, 589, L21

Marconi, A., Risaliti, G., Gilli, R., Hunt, L. K., Maiolino, R., & Salvati, M. 2004, *MNRAS*, 351, 169

Martin, D. C., *et al.* 2007, *ApJS*, 173, 342

McCarthy, P., Baum, S., & Spinrad, H. 1996, *ApJS*, 106, 281

McLure, R. J., Jarvis, M. J., Targett, T. A., Dunlop, J. S., & Best, P. N. 2006, *MNRAS*, 368, 1395

McNamara, B. & Nulsen, P. 2007, *ARAA*, 45, 117

Miley, G. K., *et al.* 2006, *ApJ*, 650, L29

Nandra, K., Georgakakis, A., Willmer, C. N. A., Cooper, M. C., Croton, D. J., Davis, M., Faber, S. M., Koo, D. C., Laird, E. S., & Newman, J. A. 2007, *ApJ*, 660, L11
Nesvadba, N. P. H., Lehnert, M. D., Eisenhauer, F., Gilbert, A., Tecza, M., & Abuter, R. 2006, *ApJ*, 650, 693
Nesvadba, N. P. H., Lehnert, M. D., Davies, R. I., Verma, A., & Eisenhauer, F. 2008a, *A&A*, 479, 67
Nesvadba, N. P. H., Lehnert, M., De Breuck, C., Gilbert, A., & van Breugel, W. 2008b, *A&A*, 491, 407
Norman, C. & Scoville, N. 1988, *ApJ*, 332, 124
Peng, C. Y., Impey, C. D., Rix, H.-W., Kochanek, C. S., Keeton, C. R., Falco, E. E., Lehar, J., & McLeod, B. A. 2006, *ApJ*, 649, 616
Pierce, C. M., *et al.* 2007, *ApJ*, 660, L19
Pope, A., Borys, C., Scott, D., Conselice, C., Dickinson, M., & Mobasher, B. 2005, *MNRAS*, 358, 149
Reichard, T., Heckman, T., Rudnick, G., Brinchmann, J., Kauffmann, G., & Wild, V. 2009, *ApJ*, 691, 1005
Ridgway, S. E., Heckman, T. M., Calzetti, D., & Lehnert, M. 2001, *ApJ*, 550, 122
Riffel, R., Storchi-Bergmann, T., Winge, C., Beck, T., & Schmitt, H. 2008, *MNRAS*, 385, 1129
Rovilos, E. & Georgantopoulos, I. 2007, *A&A*, 475, 115
Rovilos, E., Georgakakis, A., Georgantopoulos, I., Afonso, J., Koekemoer, A. M., Mobasher, B., & Goudis, C. 2007, *A&A*, 466, 119
Sadler, E., *et al.* 2007, *MNRAS*, 381, 211
Salviander, S., Shields, G. A., Gebhardt, K., & Bonning, E. W. 2007, *ApJ*, 662, 131
Schiminovich, D., *et al.* 2007, *ApJS*, 173, 315
Schinnerer, E., Eckart, A., Tacconi, L., Genzel, R., & Downes, D. 2000, *ApJ*, 533, 850
Shields, G. A., Gebhardt, K., Salviander, S., Wills, B. J., Xie, B., Brotherton, M. S., Yuan, J., & Dietrich, M. 2003, *ApJ*, 583, 124
Silverman, J. D., *et al.* 2009, *ApJ*, 696, 396
Spergel, D., *et al.* 2007, *ApJS*, 170, 377
Steidel, C., Erb, D., Shapley, A., Pettini, M., Reddy, N., Bogosavljevic, M., Rudei, G., & Rakic, O. 2010 [arXiv:1003.0697]
Storchi-Bergmann, T., Dors, O. L., Jr., Riffel, R. A., Fathi, K., Axon, D. J., Robinson, A., Marconi, A., & Ostlin, G. 2007, *ApJ*, 670, 959
Tegmark, M., *et al.* 2004, *Phys. Rev. D*, 69, 3051
Tremaine, S., *et al.* 2002, *ApJ*, 574, 740
Tremonti, C. A., Moustakas, J., & Diamond-Stanic, A. M. 2007, *ApJ*, 663, L77
Tristram, K. R. W., *et al.* 2007, *A&A*, 474, 837
Wild, V., Kauffmann, G., Heckman, T., Charlot, S., Lemson, G., Brinchmann, J., Reichard, T., & Pasquali, A. 2007, *MNRAS*, 381, 543
Wild, V., Heckman, T., & Charlot, S. 2010 [arXiv:1002.3156]
Woo, J.-H., Treu, T., Malkan, M., & Blandford, R. 2008, *ApJ*, 681, 925
Zakamska, N., Strauss, M., Krolik, J., Ridgway, S., Schmidt, G., Smith, P., Heckman, T., Schneider, D., Hao, L., & Brinkmann, J. 2006, *AJ*, 132, 1496