Cosmology, Galaxy Formation and Astroparticle Physics
on the pathway to the SKA
Klöckner, H.-R., Rawlings, S., Jarvis, M. & Taylor, A. (eds.)
April 10th-12th 2006, Oxford, United Kingdom

Quasar host galaxies

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Abstract. The discovery that the formation and evolution of supermassive black holes and their host spheroids are intimately related has given new impetus to the study of quasar host galaxies. As a result, many current studies of quasar hosts are focused on exploring the redshift evolution of the black-hole:spheroid relation, and the evolution of the massive galaxy population as a whole. This brief review of the subject begins by discussing the principal motivation behind studies of quasar hosts at the current time, before proceeding to summarise many of the important advances made in the field over the last fifteen years. Finally, current studies of quasar host galaxies are discussed, along with the prospects for important advances in the near future.

1. Introduction

The aim of this brief review article is to summarise the major advances in the field of quasar host galaxy studies over the last fifteen years, discuss the studies underway at present, and finally to consider the prospects for progress in the near future. However, before beginning, it is worthwhile considering the fundamental reasons why, despite the considerable technical challenges, the study of quasar host galaxies is now more important than ever.

Only a decade ago the aim of most quasar host galaxy observations was to address one of two fundamental, but active galactic nuclei (AGN) specific, questions. The majority of studies were simply aimed at deriving the luminosities, morphologies and characteristic sizes of quasar hosts in order to determine how these parameters related to those of "normal" quiescent galaxies. In addition, many studies were focused on determining whether differences in host galaxy properties could explain the so-called AGN radio-loudness dichotomy, whereby a minority of AGN can produce powerful radio jets, while the vast majority do not.

However, over the last five years I would argue that this situation has changed, and that the principal motivation behind many studies of quasar host galaxies today is to learn more about the formation and evolution of the massive galaxy population as a whole. There are several complementary reasons for this change of emphasis. Firstly, it has become increasingly apparent that luminous AGN, and in particular radio-loud AGN, are excellent tracers of the most massive galaxies in existence at every epoch in the Universe's history. Secondly, the discovery of the tight correlations between central black-hole mass and galaxy properties (e.g. Magorrian et al. 1998; Gebhardt et al. 2000) has made it clear that the formation and evolution of supermassive black holes and their host galaxies are intimately related. Consequently, it is now accepted that coherent models of galaxy evolution can no longer treat galaxies and quasars separately, and the latest generation of galaxy formation models now include AGN as important sources of feedback (e.g. Bower et al. 2006; Croton et al. 2006). Finally, it is worth remembering that quasars are unique in that they are the only objects for which it is possible to estimate both the galaxy *and* black-hole mass at high redshift. Consequently, the study of quasar host galaxies has a potentially crucial role to play in furthering our understanding of the evolution of massive galaxies.

2. Quasar host galaxies at low redshift

The vast majority of the progress made in our understanding of low-redshift quasar host galaxies came in the 1990s as a direct result of the stable, high spatial resolution imaging provided by the Hubble Space Telescope (HST). Following the refurbishment of HST in 1993, a variety of optical imaging studies of the host galaxies of luminous quasars at low redshift (i.e. $z \leq 0.5$) were undertaken (e.g. Disney et al. 1995; Bahcall et al. 1997; McLure et al. 1999; Schade et al. 2000; Dunlop et al. 2003). At the time it appeared that many of the results of these studies were somewhat contradictory. However, with the benefit of hindsight, it is now clear that several "consensus" results did emerge. Firstly, it became apparent that low-redshift quasar host galaxies were luminous (typically brighter than $L^{\star}$), and large (half-light radii of $\simeq 10$ kpc). Secondly, the morphology of the host galaxies of radio-loud quasars were confirmed to be exclusively early-type, in agreement with the prediction of AGN unification schemes (e.g. Urry & Padovani 1995). In contrast, radio-quiet quasars were found to reside in both early and late-type hosts. However, by combining the results of several of these low-redshift imaging studies, it becomes apparent that the fraction of radio-quiet AGN residing in early-type hosts is an increasing function of their optical luminosity (e.g. Dunlop et al. 2003). Indeed, although not obvious at the time, the changing mix of host galaxy morphologies displayed by radio-quiet quasars can now be seen as a natural consequence of the underlying correlation between black-hole and galaxy spheroidal mass. Finally, virtually

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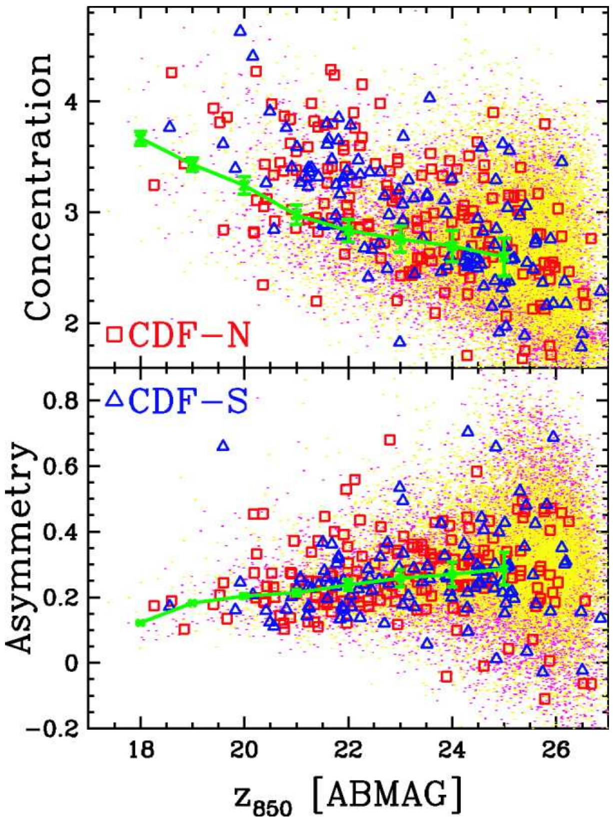

Fig. 1. A reproduction of Fig. 1 from Grogin et al. (2005). The upper and lower panels show the concentration and asymmetry parameters for a magnitude limited sample of field galaxies selected from the north and south Chandra deep fields. The solid lines show the median parameter values as a function of apparent magnitude. The squares and triangles are the host galaxies of X-ray selected AGN in the same fields. While the AGN hosts are biased towards early-type morphology (high concentration), they show now obvious bias towards greater asymmetry (merger activity).

all of the studies were in agreement and that the hosts of radio-loud quasars are systematically $\simeq 0.5$ magnitudes brighter than their radio-quiet counterparts (for samples matched in optical luminosity). Again, recent studies suggest that this host galaxy luminosity difference can be readily explained by a systematic difference in black-hole mass (e.g. McLure & Jarvis 2004).

3. Quasar host galaxies at intermediate redshift

The early studies of quasar host galaxies with HST in the 1990s inevitably concentrated on relatively small samples of often fairly extreme examples of AGN at low redshift. Over the last five years much of the progress in the field has again been provided by observations with HST, but this time tackling larger samples of lower luminosity AGN at higher redshift.

Within this context, the results of Grogin et al. (2005) based on deep HST imaging from the GOODS survey (Giavalisco et al. 2004) are a good example. Using the HST imaging data Grogin et al. were able to derive asymmetry and concentration parameters (non-parametric measures of merger activity and morphology) for a magnitude limited sample of ≥ 35000 field galaxies. Using this information as a base-line, Grogin et al. proceeded to derive asymmetry and concentration measurements for the host galaxies of $\simeq 100$ X-ray selected AGN within the GOODS fields, with redshifts of $z \leq 1.3$. In terms of asymmetry, Grogin et al. found no evidence that AGN host galaxies display more merger-type features than comparable field galaxies (Fig. 1). This result could be regarded as somewhat surprising, given that it is often assumed that galaxy-galaxy mergers play a fundamental role in triggering the AGN phenomenon. Secondly, Grogin et al. confirmed the low-redshift result that AGN have a systematic bias towards residing in relatively early-type host galaxies (compared to field galaxies of the same luminosity).

A second important example are the results on quasar host galaxies derived from the GEMS survey in the Chandra deep-field south (Sánchez et al. 2004). Based on HST ACS imaging covering an area of $\simeq 0.2$ square degrees, Sánchez et al. (2004) were able to study the host galaxy properties of 15 moderate luminosity AGN, within the redshift interval $0.5 < z < 1.1$. Again, this study also confirmed the low-redshift morphological results, finding that $\simeq 80\%$ of the AGN host galaxies in the GEMS sample had early-type morphology. However, with the advantage of imaging in two filters (V and z), Sánchez et al. were also able to place some constraints on the rest-frame $U-V$ colours of the AGN host galaxies. These results suggested that the AGN host galaxies spanned a wide range of $U-V$ colours, with many displaying bluer colours than would be expected from a passively evolving early-type stellar population. This suggests that there is at least some on-going star formation associated with the AGN activity, although at these intermediate redshifts it does not appear to involve a significant fraction of the host galaxy population by mass (1% → 5%).

4. Quasar host galaxies at high redshift

Due to the obvious technical challenges, progress on studying the properties and evolution of quasar host galaxies at higher redshifts has been slow. Perhaps the biggest steps forward were made by two studies which exploited the near-infrared capabilities of HST to investigate quasar host galaxies at $z \sim 1$ and $z \sim 2-3$ (Kukula et al. 2001; Ridgway et al. 2001). At $z \sim 1$ Kukula et al. found little evidence for evolution in the host galaxy properties when compared to the results of low-redshift studies. However, by $z \sim 2$ the results of both studies suggested that the hosts of radio-quiet quasars are a factor of $2-3$ less luminous than their low-redshift counterparts, as might be expected within hierarchical galaxy assembly.

With the useful sensitivity of HST effectively limited to $\lambda \leq 1.6\mu$m, pushing quasar host galaxy studies to $z \geq 3$ must rely on ground-based imaging in the $K-$band. In this regard, progress has definitely been much slower than might have been anticipated five years ago. One of the principle reasons behind this is the lack of success associated with adaptive optics (AO) imaging of quasars from the ground. Although numerous studies have attempted to use AO systems to observe high-redshift quasars in the past few years (e.g. Lacy et al. 2002; Croom et al. 2004; Kuhlbrodt et al. 2005) the results have been somewhat mixed. Indeed, to date the number of quasar host galaxies securely detected and resolved using AO observations is still extremely low, and AO has not produced any results which could not have been achieved in the best natural seeing. The reason for this is two-fold. Firstly, natural guide star AO imaging has a very stringent requirement for a bright guide star very close to your target (typically $\leq$ 30 arcsec), which inevitably produces very small samples of suitable AO targets. Secondly, although AO can produce point spread functions (PSFs) with very high strehl ratios, so far it has been extremely difficult to achieve the level of PSF stability which is crucial for quasar host galaxy studies. While the first of these AO drawbacks should be partially alleviated with the introduction of laser guide star AO systems, it is not clear how the fundamental problem of AO PSF stability can be satisfactorily overcome.

Indeed, it appears that perhaps the best hope of accurately studying the evolution of quasar host galaxies at high redshift is to rely on the best natural ground-based seeing, without AO correction. Although the achievable spatial resolution is inevitably lower ($\simeq 0.4$ arcsec instead of ≤ 0.1 arcsec), crucially the PSF stability is vastly improved. The viability of this technique has recently been demonstrated by Falomo et al. (2004) who were able to resolve the host galaxies of luminous quasars in the redshift interval $1 < z < 2$ using $K-$band imaging on the VLT. However, it is now clear that to study statistically significant samples of quasar host galaxies at $z \simeq 3$ and beyond will require a considerable observational effort, with each target requiring many hours of on-source integration on 8m-class telescopes.

5. The black hole - bulge correlation

Despite the difficulties of studying quasar host galaxies at high redshift, a strong scientific case can be made to justify the observational expense. The discovery of the correlation between black-hole and bulge mass in the local Universe has made it obvious that studying quasars and their host galaxies is now more important than ever. Several studies (e.g. Gebhardt et al. 2000; Ferrarese et al. 2001; McLure & Dunlop 2002) have now demonstrated that AGN host galaxies at low-redshift follow the same correlations between black-hole and bulge mass as local massive quiescent galaxies. This is an important result because if AGN host galaxies are unbiased tracers of the relationship between black-hole and galaxy mass, they can potentially be used to explore how this relationship evolves as a function of redshift. As previously mentioned, due to the so-called virial black-hole mass estimator (e.g. Kaspi et al. 2000), quasars are unique in that it is possible to estimate the mass of both the host galaxy and the central black-hole at high redshift (e.g. McLure & Jarvis 2002; Vestergaard 2002).

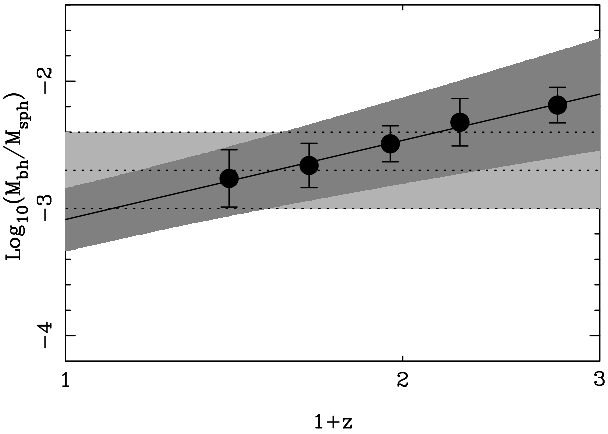

Fig. 2. A reproduction of Fig. 3 from McLure et al. (2006). The data-points show the evolution of the black-hole:bulge mass ratio as derived from the complete 3CRR sample of radio-loud AGN. The best-fitting relation (solid line) has the functional form: $\frac{M_{bh}}{M_{bulge}} \propto (1+z)^{2.07\pm0.76}$. The dark grey shaded area illustrates the expected 1σ uncertainty on the best-fitting relation. The light grey shaded area illustrates the current factor of two uncertainty on the black-hole:bulge mass ratio in the local Universe.

Currently, the first observational attempts are being made to utilise AGN host galaxies to investigate the evolution of the black-hole:bulge mass ratio as a function of redshift. The results of McLure et al. (2006) and Peng et al. (2006), based on radio-galaxies and quasars respectively, suggest that by $z \simeq 2$ the ratio of black-hole to bulge mass has increased by a factor of $\simeq 5$ compared to the locally observed value. However, it is important to note that this figure currently carries a large error bar (at least a factor of 2), and Hopkins et al. (2006) have recently presented arguments that the increase in the black-hole:bulge mass ratio by $z \simeq 2$ can be no larger than a factor of $\simeq 2$. It is clear that there are two requirements for significant progress to be made in this area. Firstly, larger samples of quasars are needed at each redshift to overcome the significant object-by-object uncertainties associated with the virial black-hole mass estimator. Secondly, deep, high-quality imaging is required at several wavelengths to further constrain the star-formation history and mass of the underlying host galaxies.

6. Conclusions

Over the last fifteen years major progress has been made in our understanding of quasar host galaxies. This progress has been at its most dramatic at low redshift, where the high spatial resolution and stable PSF of HST undoubtedly revolutionised the field. As a consequence, we now have a vastly improved knowledge of the luminosities, sizes and morphologies of the host galaxies of luminous quasars at $z \leq 1$. In contrast, I would argue that at high redshift progress has actually been substantially slower than might have been anticipated. Partly this slow progress has been due to the difficulty of producing high spatial resolution *and* PSF stability using ground-based AO imaging, and partly it has been simply due to the large commitment of observing time necessary to assemble even relatively small samples at high redshift. However, on a more positive note, two different observational approaches do show the potential to produce significant progress in the near future. At high redshift, ultra-deep K-band imaging obtained in the best natural seeing conditions should allow the evolution of quasar host galaxies to be followed out to $z \geq 3$. Finally, at low-redshift, the combination of IFU observations with the power of laser guide star AO imaging offers the opportunity to study the dynamics and starformation of quasar host galaxies in unprecedented detail.

Acknowledgements. I would like to thank the Royal Society for their funding support in the form of a University Research Fellowship.

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