The masses of AGN host galaxies & the origin of radio loudness

James S. Dunlop\textsuperscript{1} and Ross J. McLure\textsuperscript{2}

\textsuperscript{1} Institute for Astronomy, Royal Observatory, Edinburgh, EH9 3HJ, UK
\textsuperscript{2} Astrophysics, Department of Physics, Keble Road, Oxford, OX1 3RH, UK

Abstract. We highlight some of the principal results from our recent Hubble Space Telescope studies of quasars and radio galaxies. The hosts of these powerful AGN are normal massive ellipticals which lie on the region of the fundamental plane populated predominantly by massive ellipticals with boxy isophotes and distinct cores. The hosts of the radio-loud sources are on average \( \simeq 1.5 \) times brighter than their radio-quiet counterparts and appear to lie above a mass threshold \( M_{\text{sph}} > 4 \times 10^{11} M_\odot \). This suggests that black holes more massive than \( M_{\text{bh}} > 5 \times 10^8 M_\odot \) are required to produce a powerful radio source. However we show that this apparent threshold appears to be a consequence of an upper bound on radio output which is a strong function of black-hole mass, \( L_{50GHz} \propto M_{\text{bh}}^{2.5} \). This steep mass dependence can explain why the hosts of the most powerful radio sources are good standard candles. Such objects were certainly fully assembled by \( z \simeq 1 \), and appear to have formed the bulk of their stars prior to \( z \simeq 3 \).

1 Introduction

Since the optical identification of Cygnus A (Baade & Minkowski 1954) it has been clear that the host galaxies of the most powerful radio sources in the nearby universe appear to be massive ellipticals. However, it is only in the last decade, since the repair of HST, that it has proved possible to perform a detailed comparison of the hosts of powerful radio-loud and radio-quiet AGN. In this brief article we summarize some of the main results from our recent HST studies of AGN hosts, with special emphasis on how their structures, sizes, luminosities and masses compare to those of ‘normal’ galaxies. We also explore what such studies can teach us about the physical difference between radio-loud and radio-quiet AGN, and about the formation history of massive elliptical galaxies.

2 Quasar host galaxies and ‘normal’ ellipticals

One of the most important new results from this work is the discovery not only that the hosts of powerful AGN (both radio-loud and radio-quiet) are almost exclusively ellipticals, but that these galaxies display a Kormendy relation indistinguishable in both slope and normalization from that displayed by normal massive ellipticals (Fig. 1; Dunlop et al. 2002). The Kormendy relation is the photometric projection of the Fundamental Plane (Djorgovski & Davis 1987; Dressler et al. 1987), but in the case of radio galaxies the third dimension (i.e.
Fig. 1. The Kormendy relation followed by the hosts of all 33 powerful AGN imaged with the HST by Dunlop et al. (2002). The solid line is the least-squares fit to the data which has a slope of 2.90, in excellent agreement with the slope of 2.95 found by Kormendy (1977) for inactive ellipticals in the $B$-band. The dotted line has a slope of 5, indicative of what would be expected if the scale-lengths of the host galaxies had not been properly constrained.

Central stellar velocity dispersion) can be added with relative ease. This has recently been completed for a subset of 22 radio galaxies by Bettoni et al. (2002), who confirm that these objects lie towards the bright end of the same fundamental plane as defined by quiescent massive ellipticals.

The quasar hosts and radio galaxies are therefore all clearly large luminous galaxies with $L > L^*$. However, the radio-loud hosts are more cleanly confined to a definite high mass regime, with 18/20 of the radio-loud hosts in the Dunlop et al. sample having spheroid masses $> 4 \times 10^{11} M_\odot$, compared with only 4/13 of the radio quiet hosts. The results of McLure & Dunlop (2002) demonstrate that this difference can reasonably be extrapolated to a difference in central black holes masses, with the radio-loud sources being confined to black-hole masses $M_{bh} > 5 \times 10^8 M_\odot$. 

$$
\mu_{1/2} / R_{\text{mag. arcsec}^{-2}}
$$

$$
\log_{10}(r_{1/2} / \text{kpc})
$$
3 Radio-power and spheroid/black-hole mass

At first sight, these results suggest the existence of a physical mass threshold above which galaxies (or their central black holes) are capable of producing powerful relativistic jets. This would also appear consistent with long-standing suggestions of a definite gap in the radio luminosity function of optically selected quasars. However, the recent study of Lacy et al. (2001) does not support the existence of any such gap or threshold. In fact Lacy et al. demonstrate the existence of a clear, albeit loose, correlation between radio power and black-hole/spheroid mass extending over 5 decades in radio power. However, the large scatter in the data, and the relatively gentle slope of the best-fitting relation \( L_{5GHz} \propto M_{bh}^{1.4} \) do not provide an obvious explanation of why the hosts of powerful radio sources should be such good standard candles.

Instead, Dunlop et al. (2002) have suggested that the distribution of AGN on the \( L_{5GHz}:M_{bh} \) plane is better described as being bounded by a lower and upper threshold for the radio output that can be produced by a black hole of given mass, and that these radio output thresholds are a much steeper function of mass, i.e. \( L_{5GHz} \propto M_{bh}^{2.5} \). In Fig. 2 we demonstrate that the bounding relations deduced by Dunlop et al. also provide an excellent description of the data gathered by Lacy et al. In fact, the lower boundary is essentially identical to the relation derived for nearby galaxies by Franceschini et al. (1998), who also concluded in favour of \( L_{5GHz} \propto M_{bh}^{2.5} \). However, Fig. 2 makes the interesting (and perhaps surprising) point that the upper limit on black-hole radio output appears to be a similarly steep function of mass, simply offset by 5 decades in radio power.

This steep upper boundary on \( L_{5GHz} \) as a function of black-hole/spheroid mass provides a natural explanation for why the low-redshift radio-loud AGN hosts studied by Dunlop et al. lie above an apparently clean mass threshold. These objects have \( L_{5GHz} > 10^{24} \text{WHz}^{-1} \text{sr}^{-1} \), and from Fig. 2 it can be seen that such radio powers can only be achieved by black holes with \( M_{bh} > 2 \times 10^9 M_\odot \), and hence host spheroids with \( M_{sph} > 2 \times 10^{11} M_\odot \).

Fig. 2 also provides a possible explanation for why the 3CR radio galaxies at \( z \approx 1 \) appear to be even better standard candles that at low redshift; inclusion in the 3CR catalogue at \( z \approx 1 \) requires \( L_{5GHz} > 10^{26} \text{WHz}^{-1} \text{sr}^{-1} \), which Figure 3 indicates requires black holes with \( M_{bh} > 10^9 M_\odot \), and hence host spheroids with \( M_{sph} > 10^{12} M_\odot \). At such high masses the luminosity/mass function of elliptical galaxies is very steep (Kochanek et al. 2001), and so it is inevitable that any ellipticals which lie above this mass threshold will also lie very close to it.

4 The origin of radio loudness

At the other end of the radio-power scale, Fig. 2 demonstrates the surely significant fact that many of the powerful optically-selected AGN produce a level of radio output which is indistinguishable from that produced by nearby quiescent ellipticals of comparable mass. In other words, the minimum radio power relation defined by the most radio-quiet quasars is the same as that defined by
nearby ‘quiescent’ galaxies. This dramatically illustrates how very different the physical mechanisms for the production of optical and radio emission by a black hole must be, since the AGN are clearly in receipt of plenty of fuel.

These results therefore lead us to conclude that the difference between radio-loud and radio-quiet AGN cannot be explained as due to black-hole or host-galaxy mass, host-galaxy morphology, or indeed black-hole fueling rate. Rather there must be some other property of the central engine which determines whether a given object lies nearer to the upper or lower radio-power thresholds shown in Fig. 2. The only obvious remaining candidate is spin. This has been previously suggested and explored by many authors on the basis that angular momentum must surely be important for the definition of jet direction (e.g. Wilson & Colbert 1995; Blandford 2000). Here we have effectively arrived at the same conclusion by a process of elimination of the obvious alternatives.

5 The assembly of quasar host galaxies

A number of independent lines of evidence suggest that the hosts of powerful AGN formed at high redshift. This evidence is most convincing for the radio-loud population: allowing for the effects of passive evolution, radio galaxies at $z \approx 1$
The masses of AGN host galaxies

Fig. 3. A comparison of the properties of the AGN hosts with those displayed by various other types of spheroid on the photometric projection of the fundamental plane. Symbols for the quasar hosts and radio galaxies are as in Fig. 1. The stars are the data for ULIRGs and LIRGs from Genzel et al. (2001) transformed from the infrared to the $R$-band assuming $R-K=2.5$. Triangles and squares indicate the positions of 'discy' and 'boxy' ellipticals from Faber et al. (1997) after conversion to $H_0 = 50$ kms$^{-1}$Mpc$^{-1}$.

lie on the same Kormendy relation as shown in Fig. 1 (McLure & Dunlop 2000; Waddington et al. 2002), the $K-z$ relation for powerful radio galaxies appears consistent with purely passive evolution out to $z > 3$ (van Breugel et al. 1998; Jarvis et al. 2002), and strong star-formation activity in powerful radio galaxies seems largely confined to $z > 2.5$ (Archibald et al. 2001).

The picture is currently somewhat less clear for the hosts of radio-quiet quasars. The colours and off-nuclear spectra of low-redshift quasar hosts indicate that their stellar populations are predominantly old (Dunlop et al. 2002; Nolan et al. 2000; McLure et al. 1999) but there is also some evidence that the hosts of radio-quiet quasars are significantly less massive by $z \approx 2$ compared to the present day (Kukula et al. 2001; Ridgway et al. 2001). This raises the possibility that some of the low-redshift radio-quiet quasar population could be produced by the same sort of recent major mergers which power Ultra Luminous Infrared Galaxies (ULIRGS). In fact we can now begin to explore this possibility directly by combining our own results of quasar hosts with the results of near-infrared imaging and spectroscopy recently performed by Genzel et al. (2001).
While it is true that ULIRGs such as Arp220 have surface brightness profiles well-described by an $r^{-1/4}$-law, Genzel et al. have shown that such remnants lie in a different region of the fundamental plane than that which we have found to be occupied by the quasar hosts. Specifically, the effective radii of the ULIRGs is typically an order of magnitude smaller than those of the quasar hosts. Indeed one can go further and conclude that whereas ULIRGs may well be the progenitors of the population of intermediate-mass ellipticals which display compact cores and cusps (Faber et al. 1997), the quasar hosts lie in a region of the $\mu_e - r_e$ plane which is occupied by boxy, giant, ellipticals with large cores. This comparison is illustrated in Fig. 3, where we have augmented the Kormendy diagram shown in Fig. 1 with the addition of the data from Genzel et al. on LIRGs and ULIRGs, and the data from Faber et al. (1997) on ‘discy’ and ‘boxy’ ellipticals. Thus, present evidence suggests that, at least at low redshift, any ULIRG $\rightarrow$ quasar evolutionary sequence can only apply to a fairly small subset of objects.

With the advent of the Advanced Camera on HST, and high-resolution near-infrared imaging on ground-based 8-m telescopes, the next few years should see some major advances in our understanding of the properties of quasar host galaxies as a function of redshift. Fig. 3 indicates that such studies should also shed light on the formation history of the high-mass end of the present-day quiescent elliptical galaxy population.

References

1. E.N. Archibald, et al.: MNRAS 323, 417 (2001)
2. W. Baade & R. Minkowski: ApJ 119, 206 (1954)
3. D. Bettoni, et al.: A&A in press, astro-ph/0110420
4. R.D. Blandford: astro-ph/0001499 (2000)
5. S. Djorgovski & M. Davis: ApJ 313, 59 (1987)
6. A. Dressler, et al.: ApJ 313, 42 (1987)
7. J.S. Dunlop, et al.: MNRAS in press, astro-ph/0108397
8. S.M. Faber, et al.: AJ 114, 1771 (1997)
9. A. Franceschini, et al.: MNRAS 297, 817 (1998)
10. R. Genzel, et al.: ApJ 536, 527 (2001)
11. M. Jarvis, et al.: in: The mass of galaxies from low to high redshift, in press, astro-ph/0112341
12. C.S. Kochanek, et al.: ApJ 560, 566 (2001)
13. J. Kormendy: ApJ 217, 416 (1977)
14. M. Kukula, et al.: MNRAS 326, 1533 (2001)
15. M. Lacy, et al: ApJ 551, L17 (2001)
16. R.J. McLure & J.S. Dunlop: MNRAS 317, 249 (2000)
17. R.J. McLure & J. Dunlop: MNRAS in press, astro-ph/0108417
18. R.J. McLure, et al.: MNRAS 308, 377 (1999)
19. L. Nolan, et al.: MNRAS 323, 308 (2001)
20. S. Ridgway, et al.: ApJ 550, 122 (2001)
21. W. van Breugel, et al.: ApJ 502, 614 (1998)
22. I. Waddington, et al.: MNRAS, submitted
23. A.S. Wilson & E.J.M. Colbert: ApJ 438, 62 (1995)