Supermassive black holes in radio-loud AGN

Ross J. McLure

Institute for Astronomy, University of Edinburgh

Abstract

In this review the correlations between host galaxy properties and black-hole mass determined from nearby quiescent galaxies are briefly discussed, before proceeding to investigate their application to active galactic nuclei (AGN). The recent advances in estimating the black-hole masses of AGN are then reviewed, followed by an examination of the connection between black-hole mass and radio luminosity.

Key words: galaxies: fundamental parameters - galaxies: active - quasars: general - quasars: emission lines

1 Introduction

Over the last decade the combination of HST and ground-based data has led to the measurement of the black-hole masses of some 40 inactive galaxies in the nearby Universe via gas and stellar dynamics. These black-hole mass measurements have led to the discovery of correlations between black-hole mass and the properties of the surrounding host galaxy, namely bulge luminosity and stellar velocity dispersion. In parallel to the discovery of these correlations in inactive galaxies, the last few years has also seen a new industry emerge in estimating the black-hole masses of active galaxies. In the first section of this review I will discuss the recent advances in our understanding of the connection between black-hole mass and host-galaxy properties in both active and inactive galaxies at low redshift. In the second section I will proceed to discuss how black-hole mass estimation in active galaxies has been used to investigate the connection between black-hole mass and radio power.
2 The black-hole masses of nearby inactive galaxies

Within the context of the study of AGN black-hole masses, the most important aspect of the recent increase in the numbers of nearby quiescent galaxies with black-hole mass measurements has been the discovery of two correlations between black-hole mass and the properties of the surrounding host galaxy. Given the recent demonstration that at low redshift the host galaxies of all powerful AGN are indistinguishable from nearby inactive ellipticals (Dunlop et al. 2003), irrespective of radio luminosity, these correlations can now be applied to estimate the central black-hole masses of active galaxies.

The first of these correlations is between black-hole mass and the bulge luminosity of the host galaxy (Kormendy & Richstone 1992, Magorrian et al. 1998). This $M_{bh} - M_{bulge}$ correlation has the advantage of being observationally inexpensive, particularly with respect to radio galaxies, but is traditionally thought to suffer from a large associated scatter $\sim 0.5$ dex (although see below).

The second, more recently discovered, correlation is between black-hole mass and the velocity dispersion of the host galaxy stellar population (Gebhardt et al. 2000, Ferrarese & Merritt 2000). This correlation has been hailed as being the more “fundamental” due to its very low associated scatter ($\sim 0.3$ dex). However, the $M_{bh} - \sigma$ correlation, although extremely tight, has several disadvantages with respect to studying the black-hole masses of active galaxies. Firstly, even at low redshift it is not possible to obtain central stellar velocity dispersions for powerful quasars due to the presence of the unresolved nuclear point source. Furthermore, although it is possible to obtain velocity dispersion measurements for radio galaxies at low redshift, this will not be practicable at $z > 1$ even with 8m-class telescopes. Consequently, before proceeding to discuss a more direct method of estimating black-hole mass in AGN, I will digress slightly to discuss the possibility that the intrinsic scatter in the $M_{bh} - M_{bulge}$ relation is significantly lower than has previously been appreciated.

2.1 The intrinsic scatter in the $M_{bh} - M_{bulge}$ relation

It has occurred to a number of authors that the high level of scatter associated with the $M_{bh} - M_{bulge}$ relation could well be an artifact of the difficulties in determining accurate bulge luminosities for late-type galaxies. This issue is addressed in Fig 1 (taken from McLure & Dunlop 2002) which shows a comparison of the $M_{bh} - M_{bulge}$ and $M_{bh} - \sigma$ relations for a sample of 18 quiescent galaxies drawn from the list of objects with reliable black-hole mass measurements published by Kormendy & Gebhardt (2001). These 18 objects comprise
Fig. 1. A comparison of the $M_{bh} - M_{bulge}$ and $M_{bh} - \sigma$ relations for nearby inactive galaxies with pure E-type morphologies. The scatter around the best-fitting relation in both panels (solid lines) is 0.3 dex. The dashed and dot-dashed lines in the right-hand panel are the $M_{bh} - \sigma$ fits of Ferrarese & Merritt (2000) and Gebhardt et al. (2000) respectively. Figure taken from McLure & Dunlop (2002).

those objects from the Kormendy & Gebhardt compilation which have pure E-type morphology, and therefore allow an investigation of the influence of incorrectly determined bulge luminosity upon the scatter in the $M_{bh} - M_{bulge}$ relation. The best-fitting relations are shown as solid lines in both panels of Fig 1 and display an identical level of associated scatter; $\sim 0.3$ dex. This comparison demonstrates that when objects for which it is problematic to obtain accurate bulge luminosities are excluded, the scatter in the $M_{bh} - M_{bulge}$ relation is comparable to that of the $M_{bh} - \sigma$ relation. This fact has obvious consequences for the study of black-hole mass in radio-loud AGN, particularly with respect to radio galaxies for which it is straightforward to obtain relatively accurate bulge luminosities (eg. Bettoni et al. 2003). Furthermore, Graham et al. (2001) and Erwin et al. (2002) have recently demonstrated that, at least for quiescent galaxies, if sufficient care is taken over the modelling of the galaxy surface brightness profiles, then the scatter in both the $M_{bh} - M_{bulge}$ relation and a correlation between black-hole mass and galaxy light concentration is only $\sim 0.3$ dex, irrespective of morphological type.

3 Estimating black-hole masses of low redshift AGN

Although the black-hole mass - host galaxy correlations discussed above are useful for estimating the black-hole masses of AGN, there is a more direct method of black-hole mass estimation which can be applied to broad-line AGN.

This method is the so-called virial black-hole mass estimator, and utilizes the width of broad emission lines in quasar spectra to directly trace the grav-
3.1 The $M_{bh} - M_{bulge}$ relation in low redshift AGN

By utilizing the virial black-hole mass estimator it is possible to investigate whether the host galaxies of AGN do follow the same $M_{bh} - M_{bulge}$ relation as inactive galaxies in the nearby Universe (Laor 2001, McLure & Dunlop 2002).
Fig. 3. Total radio luminosity (5 GHz) versus black-hole mass for a sample of 33 AGN from Dunlop et al. (2003) and nearby quiescent galaxies from Franceschini et al. (1998). Figure taken from Dunlop et al. (2003).

2002). In Fig 2 the results of a study to investigate the $M_{bh} - M_{bulge}$ relation of 72 $z < 0.5$ AGN by McLure & Dunlop (2002) are shown. Also shown is the sample of nearby inactive galaxies with reliable black-hole mass measurements previously discussed in Fig 1. The AGN sample ($\sim 50\%$ radio-loud) consists of objects for which the host-galaxy bulge luminosity was determined via modelling of either HST or high-resolution ground-based imaging. It can clearly be seen that the AGN host galaxies follow a tight (0.4 dex scatter) correlation which is identical to that followed by nearby quiescent galaxies. Indeed, the best-fitting linear relation (dotted line) is equivalent to $M_{bh} = 0.0012 M_{bulge}$, identical to that determined by Merritt & Ferrarese (2001) for nearby quiescent galaxies.

4 The radio power - black hole mass connection

In the second section of this review I will proceed to examine recent evidence regarding the connection between black-hole mass and radio power. Figure 3 is taken from a recent paper by Dunlop et al. (2003) and shows 5 GHz radio luminosity plotted against black-hole mass for two samples. The first sample is comprised of 33 AGN, radio galaxies, radio-loud quasars and radio-quiet
quasars, who’s bulge/black-hole masses have been determined from the analysis of HST imaging. The second sample features the nearby quiescent galaxies investigated by Franceschini et al. (1998), who found a tight correlation between black-hole mass and 5 GHz radio power of the form: \( P_{\text{rad}} \propto M_{\text{bh}}^{2.5} \). In Fig 3 there are three parallel relations plotted, each of the form \( P_{\text{rad}} \propto M_{\text{bh}}^{2.5} \), separated from each other by 2.5 decades. The lowest of these three relations appears to represent a lower limit to the radio output of a black-hole of a given mass.

There are two points concerning Fig 3 which are worth highlighting. Firstly, it can be seen that many of the radio-quiet quasars from the Dunlop et al. sample lie up against the apparent radio power lower limit. This is important because the radio-quiet and radio-loud quasars were selected by Dunlop et al. to have identical optical luminosities. Consequently, it can immediately be seen that the “radio-quietness” of these quasars is not due to their central engines being starved of fuel, because they are still producing large optical luminosities. The second point refers to the hypothesized upper envelope plotted in Fig 3. Clearly, if the Franceschini-type relation does represent a lower limit to the radio output of a given black-hole mass, then it is interesting to inquire about the form of the corresponding upper envelope. Although the form of the upper envelope plotted in Fig 3 is speculative, at least based on the data from Dunlop et al., further support is provided by the data from the study of Lacy et al. (2001).

Figure 4 is an adapted version of Fig 2 from Lacy et al. (2001), which again shows the \( P_{\text{rad}} - M_{\text{bh}} \) plane, but this time populated by objects from the First Bright Quasar Survey (FBQS), the PG quasar survey and several notable low redshift objects. Figure 4 clearly demonstrates that radio power and black-hole mass are related, although a large dynamic range is required in both parameters for the relation to become apparent.

The dotted line in Fig 4 is the best-fitting relation determined by Lacy et al. (not including accretion rate as an additional parameter) and has the form \( P_{\text{rad}} \propto M_{\text{bh}}^{1.4} \). However, in order to offer an alternative interpretation of the Lacy et al. data I have annotated Fig 4 with the addition of the upper and lower limits on radio-power suggested by Dunlop et al. (2003). The lower radio power limit describes the Lacy et al. data extremely well, and again shows radio-quiet quasars lying tight up against the relation defined by quiescent galaxies, despite being well supplied with fuel. Furthermore, the Lacy et al. data also obey the upper limit on radio-power over 4 orders of magnitude in black-hole mass and 11 orders of magnitude in radio luminosity. Given that objects appear to exist between radio power boundaries spanning 5 orders of magnitude, it is therefore understandable that studies which adopt the radio-loudness parameter \( \mathcal{R} \) tend to find little or no correlation between radio-loudness and black-hole mass (eg. Woo & Urry 2002).
Fig. 4. Total radio luminosity (5 GHz) versus black-hole mass for the First Bright Quasar Survey (FBQS), the PG quasar survey and several notable low redshift objects. The black-hole masses of the quasars have been derived from the virial mass estimator. Figure adapted from Lacy et al. (2001)

One final interesting point is illustrated by Fig 4. Although there is clearly a large scatter associated with the $P_{rad} - M_{bh}$ relation, it is still true that the most radio-loud quasars are those with the most massive black-holes. For example, Fig 4 shows that quasars with $P_{rad} > 10^{25}$ WHz sr$^{-1}$ are virtually exclusively associated with black-holes of mass $> 10^9 M_\odot$. One consequence of this fact is that selecting samples based on extreme radio luminosity offers a method for selecting objects with the largest black-holes, and presumably bulge masses, at any given epoch. As a result, it should therefore be possible to cleanly trace the evolution of the $M_{bh} - M_{bulge}$ relation in a sub-set of the most massive galaxies in the Universe.

5 Conclusions

The conclusions regarding the connection between black-hole mass and radio power can be summarized as follows:

- There does not exist a threshold in black-hole mass above which an AGN must be radio-loud. There is a large overlap in the black-hole mass distri-
butions of radio-loud and radio-quiet quasars, although at a given optical luminosity radio-loud quasars do appear to be biased to higher black-hole masses than their radio-quiet counterparts.

- **Black-hole mass and radio luminosity** are connected, although an extremely large dynamic range in both parameters is required for this connection to become apparent.

- The position of an object on the $P_{\text{rad}} - M_{\text{bh}}$ plane appears to be a function of an additional physical parameter. Although accretion rate may be playing a role, the lack of a tight correlation between radio and optical luminosity suggests that some other parameter, such as black-hole spin, may be involved.

- **Selecting the most radio-loud objects, as defined by their radio luminosity alone, is an effective method of isolating the objects with the most massive black-holes, and presumably host galaxies, at any epoch.**

- **Selecting the most radio-loud objects as a function of redshift provides an ideal method for cleanly studying the evolution of the $M_{\text{bh}} - M_{\text{bulge}}$ relation within the sub-set of the most massive galaxies.**

References

[1] D. Bettoni, et al., A&A, in press, astro-ph/0212162, (2003)
[2] J. Dunlop, et al., MNRAS, in press, astro-ph/0108397, (2003)
[3] P. Erwin, et al., *Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies*, L. Ho Ed., 2002
[4] L. Ferrarese, D. Merritt, ApJ 539 (2000) L9
[5] A. Franceschini, et al. MNRAS 297 (1998) 817
[6] K. Gebhardt et al., ApJ 539 (2000) L13
[7] A. Graham et al., ApJ 563 (2001) L11
[8] J. Kormendy, D. Richstone, ApJ 393 (1992) 559
[9] J. Kormendy, K. Gebhardt, *20th Texas Symposium on relativistic astrophysics*, C. Wheeler, H. Martel Ed. 2001, p363
[10] M. Lacy, et al., ApJ 551 (2001) 17
[11] A. Laor, ApJ 553 (2001) L01
[12] J. Magorrian, et al. AJ 115 (1998) 2285
[13] R. McLure, J. Dunlop, MNRAS 331 (2002) 795
[14] D. Merritt, L. Ferrarese, MNRAS 320 (2001) L30
[15] C. Onken, B. Peterson, ApJ 572 (2002) 746
[16] B. Peterson, *Active Galactic Nuclei: from Central Engine to Host Galaxy*, S. Collin, F. Combes, I. Shlosman Ed., 2002
[17] B. Peterson, A. Wandel, ApJ 540 (2000) L13
[18] J. Woo, C. Urry, astro-ph/0211118, 2002