
Available at: [http://dx.doi.org/doi:10.1046/j.1365-8711.2000.03461.x](http://dx.doi.org/doi:10.1046/j.1365-8711.2000.03461.x)


This is the author's version of the work. It is posted here with the permission of the publisher for your personal use. No further distribution is permitted. If your library has a subscription to this journal, you may also be able to access the published version via the library catalogue.

The definitive version is available at [www.interscience.wiley.com](http://www.interscience.wiley.com)
The black hole mass – galaxy age relation

M.R. Merrifield¹, Duncan A. Forbes²,³ and A.I. Terlevich²

¹ School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD
² School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT
³ Astrophysics & Supercomputing, Swinburne University, Hawthorn VIC 3122, Australia

Received: Accepted:

ABSTRACT

We present evidence that there is a significant correlation between the fraction of a galaxy’s mass that lies in its central black hole and the age of the galaxy’s stellar population. Since the absorption line indices that are used to estimate the age are luminosity weighted, they essentially measure the time since the last significant episode of star formation in the galaxy. The existence of this correlation is consistent with several theories of galaxy formation, including the currently-favoured hierarchical picture of galaxy evolution, which predicts just such a relation between black hole mass and the time since the last burst of merger-induced star formation. It is not consistent with models in which the massive black hole is primordial, and hence uncoupled from the stellar properties of the galaxy.

Key words: Galaxies: formation, nuclei – quasars: general – black hole physics

1 INTRODUCTION

The existence of active galactic nuclei has long been taken as evidence for the existence of massive black holes in the centres of some galaxies (Lynden-Bell 1969). However, it is only relatively recently that high spatial resolution studies of the kinematics of galactic nuclei have revealed that essentially all galaxies harbour large central masses [see Ho (1999) for a review of the evidence]. The existence of these observations also means that there are now enough data to study the demographics of massive black holes, in order to seek clues to their origins.

The first significant discovery in this regard is that there is a correlation between the mass of the black hole, $M_{BH}$, and the mass of the host galaxy’s spheroidal component, $M_{sph}$. Although there is a variety of possible biases in measuring this correlation, it seems broadly to be the case that there is a linear relationship, such that $M_{BH} \sim 0.005 M_{sph}$ (Magorrian et al. 1998).

Although this correlation is reasonably strong, there is still considerable scatter in the relation, such that there is more than a factor of ten variation in the inferred value of $M_{BH}$ for galaxies of given spheroid mass (Magorrian et al. 1998). Some of this scatter can probably be attributed to the uncertainties in calculating black hole masses from relatively poor kinematic data and simplified dynamical models (van der Marel 1997). However, there are also astrophysical reasons why one might expect significant dispersion in this relation. For example, consider the simplest possible scenario in which galaxies form and evolve in near isolation. If the central black holes in these galaxies accrete mass fairly steadily from their hosts, then the mass of a black hole simply reflects the age of its host.

Under the currently-favoured hierarchical paradigm for galaxy formation, in which larger galaxies are formed from the merging of smaller galaxies (White & Rees 1978), the simple linear correlation between galaxy mass and black hole mass is readily explained. Each time two galaxies merge to form a larger system, their black holes rapidly spiral to the centre of the new galaxy due to dynamical friction. The black holes then merge, creating a proportionately-larger black hole. However, a galaxy formed by this process of repeated mergers cannot be characterized by a single age, so the above explanation for the scatter in black hole masses must be modified somewhat. One measure of such a galaxy’s age is the time since it last underwent a major merger, and Kauffmann & Haehnelt (2000) have shown that this timescale is a key factor in explaining the scatter in black hole masses. If the last merger happened long ago, then it will have occurred between relatively unevolved galaxies in which there would have been a large amount of cold gas. If the black hole accretes some fixed fraction of this gas, then galaxies in which the last merger occurred longer ago will contain more massive black holes.

This picture, in which black holes acquire much of their mass through accretion of material from their host galaxies, seems quite credible. However, it is not the only possible scenario. Stiavelli (1998) has argued that galaxies with

* The term “spheroidal component” refers to the whole system in the case of elliptical galaxies, but just the bulge in systems with significant disk components.
2 ANALYSIS

2.1 Black hole mass determinations

There are now several compilations of central black hole mass estimates in nearby galaxies (e.g. Ho 1999). The difficulty in using such compilations for quantitative studies is that they contain data obtained using a variety of heterogeneous techniques. Thus, not only are there likely to be systematic errors in the derived masses, but the nature of these errors will vary within the compilation.

To minimize the impact of such uncertainties, we have chosen to consider a sample containing only objects from a single study where the analysis has been performed in a consistent fashion. Although it could not be argued that such a sample is necessarily free of systematic errors, one might reasonably hope that the consistent analysis should produce relatively consistent results. For example, if one galaxy is found to have a more massive black hole than another optically-identical galaxy within a single sample, then it is likely that the two systems are intrinsically different; one cannot say the same if one compares two galaxies from different samples that have been analyzed using different techniques.

The largest consistently-analyzed sample available is that published by Magorrian et al. (1998). Their study of galaxies’ stellar kinematics presented estimates for the masses of the central black holes and spheroidal components of 32 galaxies. The only exceptional galaxy in this dataset is NGC 1399. The luminosity distribution of this galaxy has a very large diffuse envelope, making it one of the most extreme known examples of a cD galaxy (Schomberg 1986). It is therefore almost impossible to disentangle the mass of this extensive galaxy from the mass of the cluster that surrounds it. In fact, it is interesting to note that this galaxy lies well above Magorrian et al.’s (1998) mean relation between $M_{\text{BH}}$ and $M_{\text{sph}}$. However, if one adds to $M_{\text{sph}}$ an estimate for the total mass in the cD envelope (which was excluded from the original mass estimate), it is straightforward to place NGC 1399 right on the mean relation. Unfortunately, it is difficult to justify this ad hoc correction when one is trying to carry out a consistent analysis. Given the undesirability of such a posteriori manipulation, and the fact that such extreme cD systems are likely to have evolved by very different mechanisms from regular ellipticals, NGC 1399 has been excluded from the sample, leaving a dataset of 31 galaxies. We should, however, note that the presence of this galaxy in the sample makes no difference to the statistical significance of the conclusions presented below.

2.2 Age determinations

As with the black hole mass estimates, it is important that the galaxy age estimates be made in as consistent a manner as possible. We have therefore used values from the recent catalogue of Terlevich & Forbes (2000), which is compiled from a relatively homogeneous dataset of high-quality absorption line measurements for galaxies (e.g. Hβ, Hγ, [MgFe]). Using the stellar population model of Worthey (1994), these line indices can be used to break the age/metallicity degeneracy, thus giving separate age and metallicity estimates.

For a few galaxies not in the Terlevich & Forbes (2000) catalogue, the same line indices have been measured by Trager et al. (1998) using data of comparable quality. Combining these measurements with the Terlevich & Forbes dataset, one can obtain consistent age estimates for 23 of the galaxies in the current sample.

The line index measurements come from the galaxies’ central regions and are luminosity weighted. They are therefore dominated by the last major burst of star formation. Thus, the age estimate probably reflects the time since the galaxy’s last major merger event, which will have induced significant amounts of star formation [see also Forbes, Ponman & Brown (1998)].

2.3 The black hole mass – galaxy age relation

Figure 1 shows the fraction of each galaxy’s spheroidal component mass that resides in its central black hole as a function of the age inferred for their stellar population. There is clearly a large amount of scatter in this plot; indeed, since there are sizeable uncertainties in both the black hole mass determinations and the age estimates, one could not expect to see a tight correlation. However, there is a definite
trend in the sense that older galaxies of a given total mass contain more massive black holes: the four youngest galaxies all have black holes whose masses lie below the mean of \( M_{\text{BH}} = 0.005 M_{\text{sph}} \), while three of the four oldest galaxies lie above this line. More quantitatively, a Spearman rank test rejects the possibility that \( M_{\text{BH}}/M_{\text{sph}} \) and \( t \) are uncorrelated at > 99% confidence. The robust nature of a rank test means that the significance of this correlation does not hang on the outlying points – the same confidence level is reached if, for example, NGC 7332 is excluded from the analysis.

3 DISCUSSION

Although there does appear to be a significant correlation between measured black hole mass and galaxy age estimate, it is not necessarily astrophysical in origin. We must first consider the possibility that it arises from some systematic error in the analysis. However, the kinematic data from which the black hole masses were inferred are completely independent from the line index data that provide the age estimates. Since the line index data were not selected with this project in mind, and the black hole mass estimates played no role in the choice of sample, the selection process cannot have induced the correlation that is seen in Fig. 1. Further, the independent nature of the data sets used to measure the two ordinates means that there can be nothing in this analysis that might preferentially over-estimate the black hole masses in old galaxies, or underestimate the masses in young systems.

It should also be borne in mind that the absolute calibrations of the black hole masses and galaxy ages are significantly uncertain. In the case of the absorption line indices, for example, the age estimates are derived from spectral synthesis modelling, which remains a somewhat uncertain process, so the absolute values of the ages of two galaxies may be quite ill-determined. However, the fact that one is older than the other can be determined relatively reliably by this modelling process, so the approximate ordering of galaxy ages can be determined quite robustly. Since the Spearman rank test described above depends only on this ordering, the statistical significance of the correlation is not dependent on the details of the adopted calibration.

It would thus appear that there is an underlying astrophysical correlation between the fraction of a galaxy’s mass in its central black hole and the age of its most recently formed stellar component. Hence, in addition to the established correlation between black hole mass, \( M_{\text{BH}} \) and galaxy mass, \( M_{\text{sph}} \), there seems to be a “second parameter” correlation with the age of the youngest stellar component. At any given value of \( M_{\text{sph}} \), different age galaxies will have different values of \( M_{\text{BH}} \), so this secondary correlation must go some way toward explaining the scatter in the primary relation.

We have sought to quantify the contribution of this second parameter to the scatter in the relation between \( M_{\text{sph}} \) and \( M_{\text{BH}} \) by calculating

\[
\log(M_{\text{BH}}/M_{\text{sph}}) \approx \log(M_{\text{BH}}/M_{\text{sph}}) - \log(t/10 \text{ Gyr}) \quad (1)
\]

This process corrects the mass ratio for the effects of age by subtracting the simplest possible linear fit to the correlation in Fig. 1. As one would expect, this correction reduces the scatter in the relation: for the data in this sample, the dispersion in \( \log(M_{\text{BH}}/M_{\text{sph}}) \) is 0.42 dex while that in \( \log(M_{\text{BH}}/M_{\text{sph}})^* \) is only 0.31 dex. Clearly, even the corrected mass ratio still contains considerable scatter. However, given the large uncertainties in the individual black hole mass and galaxy age determinations, it would be very surprising if the dispersion were reduced below a factor of two (~ 0.3 dex).

The simplest explanation for the existence of the second parameter correlation is that a single physical process couples the growth of the central black hole to the triggering of star formation in a galaxy. As outlined in the Introduction, the hierarchical picture of galaxy and black hole evolution described by Kauffmann & Haehnelt (2000) suggests that galaxy mergers lie behind both processes. Where the last major merger occurred long ago, it will have taken place in a gas-rich environment that will provide ample fuel to augment the mass of the black hole. Since the last major episode of star formation will also be triggered in the merger, such galaxies will contain old stellar populations and massive black holes. Conversely, galaxies formed in more recent mergers will contain under-massive black holes and younger stellar populations.

Although the correlation between black hole mass and galaxy age is predicted by the hierarchical merging models, it should be borne in mind that such a correlation is a fairly generic prediction of any model in which the black hole mass grows over time. Even if galaxies form monolithically, those that form first – and hence contain the oldest stellar populations – will have had time to grow the largest black holes. The models that do not fit easily with this correlation are those in which the black holes and stellar components form at entirely different times – it would be hard to explain the observed correlation if, for example, the central black holes were entirely primordial.

The study of black hole demographics is maturing rapidly, and, as we hope we have shown, it is already possible to detect phenomena beyond the basic relation between \( M_{\text{BH}} \) and \( M_{\text{sph}} \). In the near future, larger sets of both the kinematic and line-strength data will become available, and more sophisticated modelling techniques will be developed to refine the estimates for black hole masses and galaxy ages. With these tools, it will become possible to address subtler questions, such as whether a galaxy’s environment plays a significant role in its black hole growth rate. Such analyses will provide key tests for theories of black hole formation within the broader context of galaxy evolution.

ACKNOWLEDGMENTS

It is a pleasure to thank the referee, Bob Mann, for a range of helpful suggestions.

REFERENCES

Lynden-Bell, D, 1969, Nat., 223, 690