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The legacy and large-scale distribution of active galaxies

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If accretion onto massive black holes is the power source for active galaxies, then nearby galaxies should contain 'dead quasars': black holes that do not shine, either because they are starved for fuel or because they accrete with low radiative efficiency. This article briefly reviews the evidence that most inactive galaxies contain black holes at their centres, and how the local distribution of black holes is related to the population of active galaxies.

Keywords: active galactic nuclei; black holes; galactic centres; quasars

1. Introduction

Most astronomers agree that the following facts are well established.

(i) The active galactic nuclei (AGN) at the centres of many galaxies are powered by accretion onto black holes (BHs) (e.g. Krolik 1999).

(ii) The comoving number density of optically luminous AGN (quasars) was roughly two orders of magnitude larger at redshift $z \simeq 2$ than it is now (Croom *et al.* 2004).

(iii) Massive BHs inevitably spiral to the centre of their host galaxy as their orbits decay from dynamical friction, on a time-scale approximately equal to

$$5 \times 10^9\ \mathrm{yr} \left(\frac{r}{10\ \mathrm{kpc}}\right)^2 \left(\frac{v_c}{250\ \mathrm{km\ s^{-1}}}\right) \left(\frac{10^8 M_\odot}{M_\bullet}\right),$$

where r is the initial orbital radius, v_c is the circular speed of the host galaxy, and $M_\bullet$ is the BH mass (Binney & Tremaine 1987, eqn 7-26).

(iv) Once settled at the galactic centre, a massive BH is difficult to dislodge, except perhaps in some cases by three-body interactions with other BHs or gravitational-radiation recoil during mergers (Merritt *et al.* 2004; Madau & Quataert 2004). Given these premises, many inactive nearby galaxies must contain BHs ('dead quasars') at their centres (Lynden-Bell 1969). The detection and characterization of these exotic objects provide considerable insight into the nature of AGN and the formation and properties of both active and inactive galaxies.

One contribution of 13 to a Discussion Meeting 'The impact of active galaxies on the Universe at large'.

2. Black holes in nearby galaxies

The closest and most convincing case of a massive BH is found at the centre of our own Milky Way galaxy, which contains a dark mass of (2–4) $\times 10^6 M_\odot$ within a radius of less than ~0.001 pc (Chakrabarty & Saha 2001; Schödel *et al.* 2002; Ghez *et al.* 2003). Even though this upper limit is still $\sim 10^3$ Schwarzschild radii, we believe that the mass must be a BH because no other known, long-lived astrophysical system of this mass could be so small. A second persuasive case is NGC4258, which contains a small (~0.2 pc) gas disc at its centre that exhibits maser spots. The kinematics (radial velocity, proper motion and acceleration) of the masers show that there is a central mass smaller than the disc and determine both its mass ($3.9 \times 10^7 M_\odot$) and the distance from the galaxy (7.2 Mpc) to an accuracy of a few per cent (Moran *et al.* 1999).

Now the literature contains ~40 nearby galaxies with detections of massive dark objects at their centres (see Tremaine *et al.* (2002) for a summary), which we believe are BHs because we know of no plausible alternative. Some of these measurements are based on the kinematics of ionized gas discs (Barth 2004), but the majority are based on stellar kinematics. Stellar-kinematic measurements have the advantage that they can be made in early-type galaxies with no dust obscuration, recent star formation, population or mass-to-light ratio gradients, all of which would complicate the interpretation; moreover stars, in contrast to gas, are never subject to non-gravitational forces. The principal limitations of stellar-kinematic investigations are that the modelling process is complicated (because the stellar distribution function, which depends on three integrals of motion, is underdetermined by the observations) and that the method is difficult to apply to the most luminous galaxies, because the stellar velocities are high, so the spectral lines are broad, the central surface brightness is low and the contributions of the stars near the BH are diluted by more distant stars in the large core of the galaxy. The current state of the art is based on orbit-superposition models (following Schwarzschild (1979)), in which a large number of orbits (the 'orbit library') is followed in a specified axisymmetric potential, and the members of the orbit library are then combined with non-negative weights to reproduce the two-dimensional surface photometry and line-of-sight velocity distribution as determined from long-slit or integral-field spectra. The goal is to determine two to three parameters: the mass-to-light ratio of the stars (assumed independent of position), the black-hole mass and sometimes the inclination of the galaxy as well.

3. Correlations with galaxy properties

The BH mass $M_\bullet$ is correlated with several properties of its host galaxy, in particular the mass M_* of the hot stellar component (Kormendy 1993)—the bulge in a spiral or S0 galaxy, or the entire stellar population in an elliptical galaxy—and the velocity dispersion σ of the hot component (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000). The correlations take the form (Häring & Rix 2004; Tremaine *et al.* 2002)

$$\begin{aligned}\log M_\bullet &= (8.20 \pm 0.10) + (1.12 \pm 0.06)\log(M_*/10^{11} M_\odot),\\ &= (8.13 \pm 0.06) + (4.0 \pm 0.3)\log(\sigma/200\ \mathrm{km\,s^{-1}}).\end{aligned} \tag{3.1}$$

The dispersion in $\log M_\bullet$ is about 0.3–0.5 from the first of these relations, and about 0.3 from the second; in both cases a substantial part of this arises from observational errors, so the intrinsic dispersion is probably smaller. These correlations hold for *all* galaxies with a hot stellar component; a BH of the expected mass has been found in every galaxy that has been examined with the required resolution. The truth of the converse, that galaxies without a hot stellar component have no central BH, is less clear: the Local Group spiral galaxy M33 has no bulge and the upper limit on any central BH is less than $1500M_\odot$ (Gebhardt *et al.* 2001), but the Magellanic spiral NGC4395 contains a Seyfert-1 nucleus and hence presumably a BH, although a small one (Filippenko & Ho 2003).

The tight correlations in equation (3.1) are important but poorly understood clues to galaxy and BH formation.

Unfortunately these correlations are determined from a rather limited baseline: half of the 31 galaxies in the sample of Tremaine *et al.* (2002) have dispersions in the small range 150–230 km s^{-1}. Fortunately, this range includes the L^* galaxies that dominate the overall mass and luminosity density of galaxies. It is important, and difficult, to extend the correlations (3.1) to both larger and smaller BH masses. At the high-mass end, we would like to find the BHs that powered the most luminous quasars, which require masses $M_\bullet \sim 3\times10^{10}M_\odot$ (based either on the assumption that the luminosity is sub-Eddington, or on empirical relations between luminosity and the size of the broad-line region (Netzer 2003)). The corresponding velocity dispersion implied by equation (3.1) is $\sigma \simeq 750$ km s^{-1}, and based on plausible estimates for the number density and duty cycle of bright quasars the nearest such galaxies should lie well within 100 Mpc. However, such galaxies should have been detected in the Sloan Digital Sky Survey and have not; for example, the largest dispersion in the $\sim10^4$ galaxy sample of Bernardi *et al.* (2003) is 400 km s^{-1}. Perhaps the mass-dispersion relation is steeper at high masses.

There is suggestive evidence that the mass-dispersion relation of equation (3.1) extends to lower masses: there are plausible measurements of BH masses in the range $10^{3.5}M_\odot$–$10^{5.5}M_\odot$ in the Galactic globular cluster M15 (Gerssen *et al.* 2002), the M31 globular cluster/dwarf galaxy core G1 (Gebhardt *et al.* 2002), the Magellanic spiral Seyfert-1 galaxy NGC4395 (Filippenko & Ho 2003) and the dwarf elliptical Seyfert-1 galaxy POX 52 (Barth *et al.* 2004). However, the globular cluster detections are controversial; the BH mass determinations in the galaxies are based on photoionization modelling of the broad-line region and other indirect arguments rather than stellar kinematics; and it is not clear how to define the velocity dispersion of the hot component in a bulgeless disc galaxy such as NGC4395.

4. Demographics

Armed with the correlations in equation (3.1), we can investigate the demographics of BHs in the local universe. The most important statistic is the local density of BHs, $\rho_\bullet$, which can be estimated by combining the $M_\bullet$–M_* relation with the luminosity function of early-type galaxies and estimates of the mass-to-light ratio of these galaxies, or by combining the $M_\bullet$–σ relation with the velocity dispersion distribution of early-type galaxies (Sheth *et al.* 2003). Two recent estimates (both for $H_0 = 70$ km s^{-1} Mpc^{-1}) are $(2.9\pm0.5)\times10^5M_\odot$ Mpc^{-3} (Yu & Tremaine 2002) and $(4.6^{+1.9}_{-1.4})\times10^5M_\odot$ Mpc^{-3} (Marconi *et al.* 2004).

These estimates can be compared with the density of BHs representing the 'ash' from extinct AGN, ρ_{AGN}, which is obtained by integrating the redshift-dependent

AGN luminosity function (Croom *et al.* 2004) and assuming an efficiency, ϵ, which is the ratio of the energy output of the AGN to the rest-mass energy of the fuel that it consumes (ρ_{AGN} scales as $(1-\epsilon)/\epsilon$). This estimate is independent of the merger history of the BHs so long as mergers conserve mass, that is, so long as the energy emitted by gravitational radiation during a merger is negligible compared with the rest-mass energy of the BHs; it is also independent of the cosmological model (Sołtan 1982). The principal uncertainty is the bolometric correction required to convert the luminosity of the AGN in the survey waveband to its bolometric luminosity; for optical surveys the bolometric correction is large, typically $10 \overset{\times}{\div} 2$, so it is important to get it right. A particularly vexing limiting case is the obscured AGN, which do not appear in optical surveys at all and hence have infinite bolometric corrections. Fortunately, Compton-thin obscured AGN can be detected by X-ray surveys and the redshifts of their host galaxies can then be determined optically, so reasonably reliable estimates of their contribution to ρ_{AGN} have recently become available. For example, Fabian (2004) finds $\rho_{\mathrm{AGN}} = 4 \times 10^5 M_\odot\ \mathrm{Mpc}^{-3}$ and Marconi *et al.* (2004) find $\rho_{\mathrm{AGN}} = (5-10) \times 10^5 M_\odot\ \mathrm{Mpc}^{-3}$, both for $\epsilon = 0.1$.

The estimates of $\rho_\bullet$ and ρ_{AGN} are consistent if the efficiency $\epsilon \simeq 0.1$–0.3; it is gratifying that this is just the range of efficiencies expected for thin-disc accretion onto rotating BHs. However, this striking agreement is a recent development. Before 2000, the local density of BHs was too high compared with the expected density of AGN ash. This was partly because estimates of $\rho_\bullet$ were mostly based on simple isotropic models of the stellar distribution function (Magorrian *et al.* 1998), which led to a modest overestimate of $M_\bullet$ (the mean overestimate in $\log M_\bullet$ was 0.2 or a factor of 1.7; see Gebhardt *et al.* (2003)). At about the same time that more accurate mass estimates became available (Gebhardt *et al.* 2000, 2003), it was recognized that the obscured AGN that contribute to the X-ray background also make a substantial contribution to ρ_{AGN} (Fabian & Iwasawa 1999), thereby increasing ρ_{AGN} by a factor of four or so, so that it now exceeded $\rho_\bullet$. However, this result was based on the assumption that the redshift distributions of the obscured and unobscured AGN were the same, and as the X-ray background was resolved into sources it became clear that the obscured AGN are at much lower redshifts ($z \sim 0.7$ compared with $z \sim 2$). This reduces the contribution of obscured AGN to ρ_{AGN} by a factor of about three, so the agreement with $\rho_\bullet$ turns out to be just right, at least for now.

With more ambition, or more hubris, it is possible to compare not just the normalization but also the shape of the local distribution of BH masses with the expectations for AGN ash (Small & Blandford 1992). To do so requires two important additional ingredients: some assumption about the relation between the bolometric luminosity and the BH mass, and some estimate of the merger history of the BHs. The simplest of these models assumes that the luminosity is a fixed fraction λ of the Eddington luminosity and that mergers have a negligible effect on the mass distribution; using these assumptions Marconi *et al.* (2004) find a good fit to the observed BH mass distribution for $\epsilon \simeq 0.1$ and $\lambda \simeq 0.5$, while Yu & Tremaine (2002) argue that more elaborate models are required, for example, one in which the efficiency is higher for high-mass BHs than for low-mass ones. A more general approach that accounts for the poorly understood merger history of BHs is to work with inequality constraints on the mass distribution that reduce to equalities when mergers are negligible (Yu & Tremaine 2002).

A quite different approach is to generalize semi-analytic galaxy-formation models to follow the evolution of the BH mass distribution. One assumes first that 'seed' BHs form at the centres of dark haloes at high redshift; the evolution of the seed BHs is determined by the merger history of the dark haloes, together with prescriptions for the fate of the BHs during a halo merger (e.g. do the BHs merge? Is total BH mass conserved during the merger?) and for the accretion of gas onto the BHs (e.g. every major merger leads to the accretion of a gas mass that is a fixed function of the halo mass). Such models can successfully reproduce a wide range of observations, including the local BH mass distribution, correlations between BH mass and galaxy properties such as the $M_\bullet$–σ relation, and the AGN luminosity function and its dependence on redshift (Haehnelt & Kauffmann 2000; Volonteri *et al.* 2002; Di Matteo *et al.* 2003). As usual, the principal limitation of these models is that they require a fairly large number of ad hoc assumptions, so their physical relevance is difficult to assess.

5. Summary

Future observational progress will include more sophisticated dynamical modelling of the centres of galaxies containing BHs (in particular, fitting better models of gas kinematics to data), and the extension of searches for BHs to more high- and low-luminosity galaxies as well as more late-type galaxies, all of which are under-represented in the current samples. Unresolved theoretical issues include: whether BHs merge efficiently when their haloes merge, or if not, what are the expected properties of binary BHs (Begelman *et al.* 1980; Yu 2002); whether gravitational radiation recoil or three-body encounters can eject merging BHs from galactic centres; and why BH mass appears to be so tightly correlated with the properties of the host galaxy.

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Discussion

J. BINNEY (*Rudolf Peierls Centre for Theoretical Physics, University of Oxford, UK*). You mention the possibility of black hole ejection from galaxies. Would this not make the problem of making luminous quasars in sufficient numbers worse, because a galaxy would just be ready to contribute a luminous quasar when its black hole was ejected and it had to start over building one up by swelling the numbers of low-luminosity quasars?

S. TREMAINE. The sign of the effect depends on whether the black hole is ejected before or after the quasi-stellar object (QSO) phase. In most cases the decay time of a binary black hole formed in a galaxy merger is much longer than the QSO lifetime, so ejection would probably occur after the QSO activity stimulated by the merger had died away.

J. P. OSTRIKER (*Institute of Astronomy, University of Cambridge, UK*). You concluded that when the black holes are radiating electromagnetic energy, i.e. they are 'on', they radiate at close to the Eddington value. But clearly most black holes in most galaxies are *not* radiating at that level; thus, they are not 'on'. What is your estimate of the time fraction spent in the 'on' state, i.e. the 'duty cycle'?

S. TREMAINE. The duty cycle is about 0.01–0.003 (Yu & Tremaine 2002). This is roughly the ratio of the Salpeter time to the Hubble time. The Salpeter time is the time required for a black hole accreting with the Eddington luminosity to e-fold in mass, and equals $4.5 \times 10^7\ \mathrm{yr}(\epsilon/0.1)$, where ϵ is the efficiency.

C. S. FRENK (*Institute for Computational Cosmology, Department of Physics, Durham University, UK*). What is the smallest galaxy mass for which there is reliable information on black hole masses and are there any prospects for improving the limits?

S. TREMAINE. The compact elliptical galaxy M32 has a black-hole mass of $(2.5 \pm 0.5) \times 10^6 M_\odot$ (Verolme *et al.* 2002). The prospects for direct measurements of black-hole masses in smaller galaxies are dim, but there are plausible dynamical detections of smaller black holes in globular clusters and indirect detections of small black holes in dwarf galaxies (see discussion at the end of § 3).

Additional reference

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