The importance of radio sources in accounting for the highest mass black holes

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Abstract

The most massive black holes lie in the most massive elliptical galaxies, and at low-$z$ all radio-loud AGNs lie in giant ellipticals. This strongly suggests a link between radio-loudness and black hole mass. We argue that the increase in the radio-loud fraction with AGN luminosity in optically-selected quasar samples is consistent with this picture. We also use the ratio of black holes today to quasars at $z \sim 2$ to conclude that the most bolometrically-luminous AGN, either radio-loud or radio quiet, are constrained to have lifetimes $\leq 10^8$ yr. If radio sources are associated with black holes of $\gtrsim 10^9 M_\odot$ at all redshifts, then the same lifetime constraint applies to all radio sources with luminosities above $L_{5\text{GHz}} \sim 10^{24}$ W Hz$^{-1}$ sr$^{-1}$.

1 Introduction

Only $\sim 10\%$ of quasars in optically-selected samples are radio loud. This fraction does, however, seem to be a function of quasar luminosity. Goldschmidt et al. (1999) show that the radio-loud fraction (where radio-loud is defined as having a 5GHz radio luminosity $L_{5\text{GHz}} > 10^{24}$ W Hz$^{-1}$ sr$^{-1}$) increases with quasar luminosity from about 10\% at $M_B = -26$ to around 40\% at $M_B = -28$ (Fig. 1). As can be seen from the figure, this does not seem to be due simply to the radio-quiet quasars becoming more radio-luminous with increasing AGN luminosity and crossing the threshold into radio loudness (as even radio-quiet

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Fig. 1. Figure 5 of Goldschmidt et al. 1999, modified to indicate the areas occupied by the radio-selected 3C and 7C quasar samples (Willott et al. 1998). The radio-selected samples naturally favour radio-brighter objects at a given optical luminosity, explaining their offset towards the top of the plot.

Quasars are not radio silent, but to a genuine increase in the relative numbers of the powerful \((L_{5\text{GHz}} > 10^{25}\text{WHz}^{-1}\text{sr}^{-1})\) radio sources.

In this paper, we combine this observation with recent studies showing that the masses of the spheroidal components of galaxies and the mass of the central black hole are correlated (Magorrian et al. 1998; van der Marel 1999). Since at low-z all radio-loud AGNs lie in giant ellipticals, this is strongly suggestive of a connection between radio-loudness and black hole mass. Thus we can now begin to speculate on the importance of radio-loud objects in the evolution of the most massive black holes.

2 Assumptions

As is usual, we characterise the accretion process in quasars in terms of two parameters, the accretion efficiency \(\epsilon\), usually assumed to be \(\sim 0.1\), and the ratio of the accretion rate to that at the Eddington limit, \(\lambda\). We assume a bolometric correction to B-band of 12 (Elvis et al. 1994) giving a B-band
quasar absolute magnitude for a black hole of mass $M_h$ of

$$M_{B,Q} = -26.2 + 2.5\lg \lambda - 2.5\lg (M_h/10^9 M_\odot).$$

The spheroid luminosity, using van der Marel (1999) relation converted into $B$-band magnitudes assuming $B - V = 0.9$, is:

$$M_{B,\text{Host}} = 0.555 - 2.5\lg (M_h/M_\odot).$$

We take $H_0 = 50 \text{km} \text{s}^{-1} \text{Mpc}^{-1}$ and $\Omega = 1$ throughout.

3 Comparing the numbers of black holes to quasars

By ratioing the number density of black holes of a given mass (from Salucci et al. 1999) with the number density of quasars at the peak of AGN activity at $z = 2$ and assuming Eddington-limited accretion, one can estimate the quasar duty cycle (Fig. 2). Given that the quasar epoch lasts for $\approx 10^9$ yr, this can be converted to a quasar lifetime assuming a single burst of activity (Richstone et al. 1998).

The uncertainties in the comparison are large, however, and the ratios should only be considered order of magnitude estimates. The comparison depends on the ratio of the high luminosity/mass ends of two very steeply declining functions. Consequently the ratio of number densities is very sensitive to errors in the calibration of the black hole mass to bulge and quasar luminosity relations. Also any intrinsic scatter in the black hole mass – bulge mass relation will tend to raise the black hole to quasar ratio when integrating the mass function from a lower bound in black hole mass. Finally, the number density of any heavily obscured radio-quiet “quasar-2” population, which is probably required to explain the hard X-ray background, is uncertain. It may be about the same as the normal quasar population (Salucci et al. 1999). If so it would be comparable to the ratio of luminous radio galaxies (i.e. the radio-loud quasar-2s) to radio-loud quasars and the ratio of type 1 to type 2 Seyferts. However, Fabian (1999) suggests that quasar-2s could be ten times more common than quasar-1s.

4 The most luminous objects

Goldschmidt et al. (1999) show that the number densities of radio-loud and radio-quiet quasars become comparable at $M_{B,Q} \approx -28$. This corresponds to
a black hole of mass $\approx 5 \times 10^9 M_\odot$ for $\lambda = 1$, or a host luminosity today of $M_B \approx -23.7$, at the top end of the observed galaxy luminosity function and consistent with the most optically-luminous FRI hosts seen today. The number density of these black holes is $\sim 10^{-6} \text{Mpc}^{-3}$.

Using the quasar luminosity function of Goldschmidt & Miller (1998) we obtain a number density of these objects at $z = 2$ of $\approx 2 \times 10^{-8} \text{Mpc}^{-3}$ (comoving), a factor of $\approx 50$ lower than the number density of corresponding black holes now. Adding the obscured population will raise the number density by a factor of 2-10, resulting in a total of $\sim 10^{-7} \text{Mpc}^{-3}$. This is an order of magnitude less than the number density of corresponding black holes in the local Universe, but is a smaller ratio than for the black holes powering quasars close to the break in the black hole mass function where the ratio is around 100 (Fig. 2), and perhaps as high as 1000 (Richstone et al. 1998).

The similarity in number densities of radio-loud and radio-quiet objects at these luminosities (unless we assume a very large population of radio-quiet quasar-2s) allows us to constrain the lifetimes of the radio-loud objects in a similar manner to those of the radio-quiets. If they had very disparate lifetimes one class or the other would dominate the mass accretion and produce objects with giant black holes, which are not seen (so far) whilst the other class would be unable to accrete a significant fraction of their black-hole mass.
Thus we conclude that all the most luminous quasars, regardless of type, have duty cycles $\sim 0.1$, meaning a maximum active lifetime of $\sim 10^8$ yr. This agrees with radio source ages based on lobe expansion speed estimates (Scheuer 1995), and allows a moderate amount of growth of the black hole as a black hole increases in mass by a factor $e$ every $t_S = 4 \times 10^7(\epsilon/0.1)$ yr.

5 Lower luminosity objects

As the quasar luminosity decreases, the radio fraction drops off rapidly, to only $\sim 10\%$ at $M_B > -26$. Why? At low redshifts radio galaxies are seen in giant elliptical hosts, but low luminosity radio-quiet quasars can be found in either ellipticals or spirals, e.g. McLure et al. 1998. Perhaps radio-loud objects are found exclusively associated with massive (and therefore rare) $> 10^9 M_\odot$ black holes, accreting at sub-Eddington rates whereas low-luminosity radio-quiets continue to be associated with Eddington or near-Eddington accretion onto less massive (and therefore much more common) black holes. This picture is supported by stored energy arguments (Rawlings & Saunders 1991), which suggest $M_h \gtrsim 10^8 M_\odot$ in even low luminosity FRII radio sources.

The number density of $L_{5\mathrm{GHz}} > 10^{24}$ WHz$^{-1}$sr$^{-1}$ radio sources is $\approx 5 \times 10^{-6}$, $\approx 20$ times lower than the number density of $> 10^9 M_\odot$ black holes. Thus radio sources with $L_{5\mathrm{GHz}} \sim 10^{24}$ WHz$^{-1}$sr$^{-1}$ accreting with $\lambda \sim 10^{-3}$ would have duty cycles again constrained to be about $10\%$, implying lifetimes $\sim 10^8$ yr. An interesting alternative possibility is that these low luminosity sources are the $90\%$ of the very massive ($> 3 \times 10^9 M_\odot$) black holes which have $\lambda \ll 1$ at $z \sim 2$. This would allow them to have duty cycles $\sim 1$ and lifetimes $\sim 10^9$ yr, which would, however, be rather longer than other radio source lifetime estimates.

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