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The Local Black Hole Mass Function from 2dFGRS Radio Galaxies

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Abstract

Radio emission from early–type (E and S0) galaxies usually signals the presence of a central supermassive black hole. If radio luminosity and black–hole mass are correlated, then we can use the large sample of radio galaxies observed in the 2dF Galaxy Redshift Survey (2dFGRS) to estimate the local ($z < 0.1$) black–hole mass function for early–type galaxies.

Integrating over this mass function yields a local black–hole mass density of $\rho_{\rm BH} = 1.8^{+0.4}_{-0.6} \times 10^5 \, M_\odot$ Mpc^{-3} (H_0 = 50 km s^{-1} Mpc^{-1}, Ω_0=1), in good agreement both with the local value derived from galaxy velocity dispersions and with the high–redshift value derived from QSOs. This supports earlier suggestions that local radio galaxies are the direct descendants of most or all of the high–redshift QSOs.

1.1 Does Radio Luminosity Scale with Black Hole Mass?

The relationship between black–hole mass and radio luminosity in nearby galaxies is currently a topic of much debate. Auriemma et al. (1977) first showed that (optically) brighter elliptical galaxies are more likely to be radio sources, so the discovery of a correlation between black–hole mass and bulge luminosity (Magorrian et al. 1998) means that some correlation between black–hole mass and radio luminosity must exist for early–type galaxies, at least in a statistical sense (there may still be considerable scatter for individual objects).

Franceschini, Vercellone & Fabian (1998) found a remarkably tight relationship between black–hole mass and radio power ($P_{\rm radio} \propto M_{\rm BH}^{2.5}$) in nearby galaxies, implying that the total radio power emitted by a galaxy is both an excellent tracer of the presence of a supermassive black hole and a good estimator of its mass. However, analysis of larger data sets by Laor (2000) and Ho (2002) found a much larger scatter in the $M_{\rm BH}$–$P_{\rm radio}$ correlation. All these authors used data sets which contained a mixture of galaxy types (e.g. spirals, ellipticals, Seyfert galaxies, radio galaxies and quasars).

More recently, Snellen et al. (2003) have investigated the correlation between black–hole mass and radio power for the large sample of nearby elliptical galaxies with stellar velocity dispersions measured by Faber et al. (1989). They found that that most optically–selected (i.e. 'relatively passive') elliptical galaxies obeyed the Franceschini et al. (1998) relation between black–hole mass and radio luminosity.

Black hole mass is clearly not the only variable which determines radio luminosity — we know that radio galaxies were more powerful and/or more numerous in the past, whereas the mass of their central black holes can only increase with time. Lacy et al. (2001) suggest that radio power scales with both black–hole mass and accretion rate, which provides a plausible mechanism for time–varying radio emission.

1.2 The 2dF Galaxy Redshift Survey

The recently-completed 2dF Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) obtained optical spectra and redshifts for over 220,000 galaxies in the local ($z < 0.3$) universe. Cross-matching these galaxies with sensitive all–sky radio imaging surveys like the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) makes it possible to assemble samples of several thousand radio-galaxy spectra which can be used to derive accurate radio luminosity functions for both AGN and star-forming galaxies (Sadler et al. 2002).

Cross-matching the 2dFGRS and NVSS surveys provides a data set which is both large and very homogeneous in quality. Although only about 1.5% of 2dFGRS galaxies are matched with radio sources above the NVSS detection limit of 2.5 mJy at 1.4 GHz, this still represents one of the largest and most uniform set of radio–galaxy spectra so far obtained. The high quality of most of the 2dFGRS spectra means that it is usually straightforward to determine whether the radio emission arises mainly from an AGN, or from processes related to star formation. The final data set (work in progress) will be a factor of four larger.

Most 2dFGRS–NVSS radio galaxies (at least 90% of those classified as AGN) show either an absorption–line spectrum typical of giant ellipticals or LINER–like emission lines superimposed on a stellar continuum, i.e. they fall into the class of 'relatively passive' radio galaxies discussed by Snellen et al. (2003). It therefore seems reasonable to use the relation between black–hole mass and radio power from Franceschini et al. (1998) together with the accurate local radio luminosity function from the 2dFGRS–NVSS sample to estimate the local mass function for massive black holes. This calculation only requires that the Franceschini et al. (1998) relation holds in a statistical sense (there can still be some scatter for individual objects) for early–type galaxies with relatively quiescent optical spectra.

1.3 The Local Radio Luminosity Function for 2dFGRS Radio Galaxies

Figure 1.1 shows the local radio luminosity function for active galaxies at 1.4 GHz, as derived by Sadler et al. (2002). The values are in good agreeement with earlier determinations, but have much lower error bars in the luminosity range 10^{22} – 10^{25} W Hz^{-1}. Remarkably, the space density of radio–emitting AGN is extremely close to a simple power–law of the form

$$\Phi(P_{1.4}) \propto P_{1.4}^{-0.62\pm0.03} \tag{1.1}$$

over almost five decades in luminosity from $10^{20.5}$ to 10^{25} W Hz^{-1}, before turning down above 10^{25} W Hz^{-1}.

1.4 The Local Black Hole Mass Function for Early-type Galaxies

Following the precepts of Franceschini et al. (1998), the 1.4 GHz radio luminosity function in Figure 1.1 can be converted to a black hole number density assuming

$$\log_{10} M_{\rm BH}\ (M_\odot) = 0.376\ \log_{10} P_{1.4}\ ({\rm W\,Hz^{-1}}) + 0.173. \tag{1.2}$$

Figure 1.2 shows the results — the downturn in the radio luminosity function above 10^{25} W Hz^{-1} implies a corresponding steeper downturn in the space density of black holes more

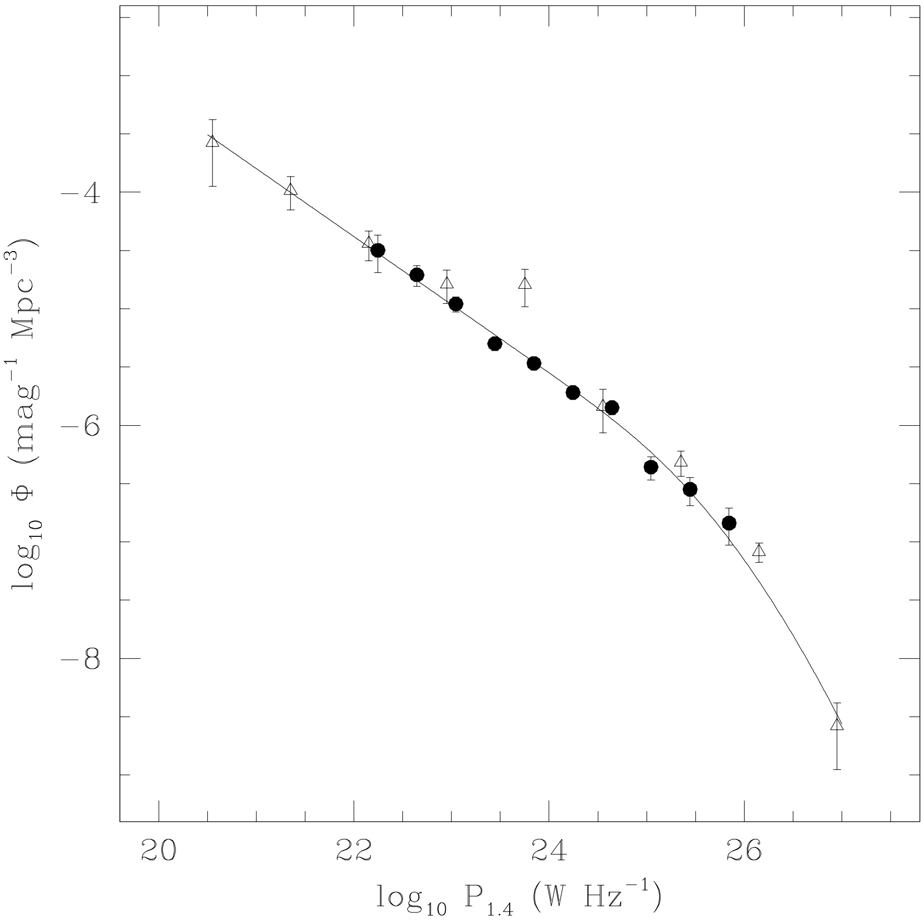

Fig. 1.1. Local radio luminosity function for active galaxies at 1.4 GHz. Filled circles are points from the 2dFGRS–NVSS data set, while open triangles are the Sadler et al. (1989) values for nearby E/S0 galaxies, converted from 5 GHz assuming a spectral index of α = −0.7. The solid line shows the best–fitting value of an analytic fitting function as described by Saunders et al. (1990). Luminosities are calculated using H_0 = 50 km s^{-1} Mpc^{-1} and Ω_0=1.

massive than about $5 \times 10^9\ M_\odot$. The derived number densities mostly agree well with the values derived by Franceschini et al. (1998), though the 2dFGRS–NVSS points are systematically higher at the high–mass end. This may be the result of luminosity evolution within the relatively large volume (to $z \sim 0.2$) probed by the 2dFGRS for powerful radio sources.

Figure 1.3 shows the mass density distribution, i.e. the number density of black holes of a given mass multiplied by that mass. Again, there is a stronger downturn above a few times 10^9 solar masses. At the low–mass end, the mass density of black holes continues to increase down to the lowest values (a few times $10^7\ M_\odot$) probed by radio surveys. Integrating over the curve in Figure 1.4 gives the total mass density of massive black holes ($M_{\rm BH} > 7.6 \times 10^7\, M_\odot$) in nearby galaxies:

$$\rho_{\rm BH} \;=\; 1.8^{+0.4}_{-0.6} \times 10^5\, M_\odot\ {\rm Mpc}^{-3} \tag{1.3}$$

This is clearly a lower limit, since the derived black–hole mass density is still increasing at the lowest values of $\rm M_{BH}$ we can measure. However, our value for $\rho_{\rm BH}$ agrees well with the values recently derived by Yu & Tremaine (2002) and Aller & Richstone (2002) from optical measurements of galaxy velocity dispersions.

It is also within the range $1.4-2.2\times10^5$ derived by Chokshi & Turner (1992) from the optical luminosity function of QSOs, implying that local radio–emitting AGN are the direct descendants of most or all of the high–z QSOs. Similar conclusions have been reached by others (e.g. Franceschini et al. 1998; Salucci et al. 1999; Merritt & Ferrarese 2001).

1.5 Conclusions

Both massive black holes and low–power radio sources are common in nearby elliptical galaxies. If radio luminosity is a good estimator of black–hole mass in these galaxies, then a comparison of the black–hole mass density in nearby early–type galaxies and distant QSOs suggests that local radio-emitting AGN (i.e. luminous elliptical galaxies) are the direct descendants of most or all of the distant QSOs.

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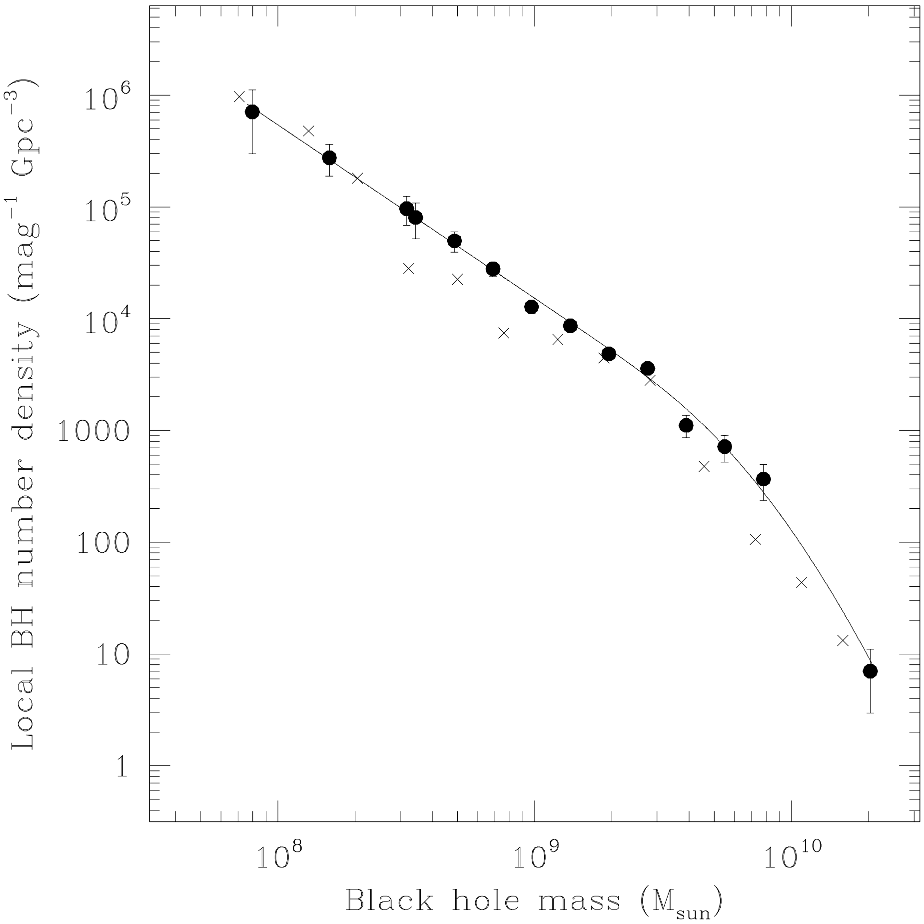

Fig. 1.2. Black hole number density, in mag^{-1} Gpc^{-3} for radio galaxies in the local universe. The filled circles and solid line are converted from the data points and analytic fit shown in Figure 1.1. Crosses show values from Franceschini et al. (1998).

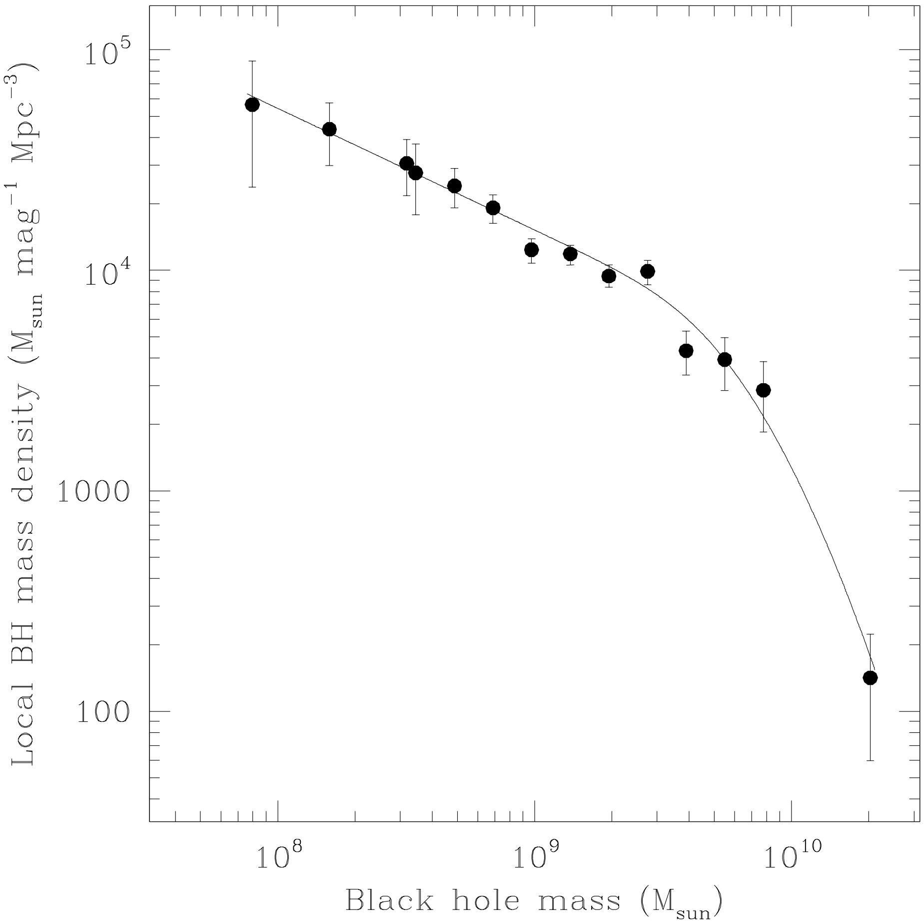

Fig. 1.3. Local black–hole mass density (in $M_\odot$ mag^{-1} Mpc^{-3}). As in Figure 1.2, the filled circles and solid line correpond to the data points and fit from Figure 1.1.