The fraction of galaxies that contain active nuclei and their accretion rates

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ABSTRACT

We investigate the relationship between the present-day optical luminosity function of galaxies and the X-ray luminosity function of Seyfert 1s to determine the fraction of galaxies that host Seyfert 1 nuclei and their Eddington ratios. The local type 1 active galactic nuclei (AGN) X-ray luminosity function is well reproduced if $\sim 1$ per cent of all galaxies are type 1 Seyferts which have Eddington ratios of $\sim 10^{-3}$. However, in such a model the X-ray luminosity function is completely dominated by AGN in E and S0 galaxies, contrary to the observed mix of Seyfert host galaxies. To obtain a plausible mix of AGN host galaxy morphologies requires that the most massive black holes in E and S0 galaxies accrete with lower Eddington ratios, or have a lower incidence of Seyfert activity, than the central black holes of later-type galaxies.

Key words: accretion, accretion discs – galaxies: active – galaxies: luminosity function, mass function.

1 INTRODUCTION

Accretion on to a massive black hole has remained the standard paradigm for active galactic nuclei (AGN) for several decades (e.g. Lynden-Bell 1969; Rees 1984). In recent years, a considerable amount of evidence has accumulated for the existence of massive black holes in many, perhaps all, galaxies (Magorrian et al. 1998; Kormendy & Richstone 1995). The connection between the formation and evolution of massive black holes and their host galaxies is currently the subject of great interest and investigation (e.g. Cattaneo, Haehnelt & Rees 1999; Fabian 1999; Salucci et al. 1999).

The luminosity function of AGN has been used for many years to track the statistical evolution of the AGN population with cosmic epoch, but does not allow a distinction between a relatively small population of long-lived AGN or many short-lived generations of AGN. The Eddington ratio, i.e. the ratio of the luminosity of an object to its Eddington luminosity, was proposed to be a powerful discriminator of AGN activity patterns by Cavaliere & Padovani (1988) with long-lived AGN having low Eddington ratios ($\sim 10^{-4}$) and short-lived AGN having high Eddington ratios ($\sim 1$). In a variety of wavebands, from radio to X-ray, the luminosity function of AGN has a characteristic two-power-law shape with a knee dividing the low- and high-luminosity objects (e.g. Boyle, Shanks & Peterson 1988; Dunlop & Peacock 1992; Page et al. 1997). It has an obvious resemblance to the luminosity function of galaxies, which is not surprising since AGN are found in galaxies. Only a few attempts have been made to relate the galaxy and AGN luminosity functions, predominantly in the form of models for the joint formation of galaxies and AGN (e.g. Haehnelt & Rees 1993; Kauffmann & Haehnelt 2000; Monaco, Salucci & Danese 2000) yet the direct comparison of galaxy and AGN luminosity functions can shed light on two fundamental properties of the black hole population: the fraction of massive black holes which are active, and their Eddington ratios. This is the subject of this paper.

Throughout we have taken $q_0 = 0$ and $H_0 = 100 \, h \, \text{km s}^{-1} \, \text{Mpc}^{-1}$.

2 METHOD

2.1 The relationship between galaxy and AGN luminosity functions

The luminosity function of AGN must be related to the mass function of massive black holes. If the masses of central black holes are related to the masses of their host galaxy bulges (Kormendy & Richstone 1995; Magorrian et al. 1998), then the luminosity functions of AGN and galaxies must be strongly related. This is modelled in the following formalism.

We define the luminosity function as

$$\phi = \frac{d^2N}{dVdL},$$

where $N$ is the number of objects, $V$ is the comoving volume and $L$ is the luminosity, and start from the luminosity functions $\phi_i$ of galaxies of $n$ different morphological types $i$. We assume that the spheroid components of galaxies of type $i$ produce a fraction of their light $f_{\text{shb}}(i)$. We can then translate from the $\phi_i$ to a spheroid.
luminosity function $\phi_{\text{sph}}$ by

$$\phi_{\text{sph}}(L_{\text{sph}}) = \sum_{i=1}^{n} \phi_i [L_{\text{sph}}/f_{\text{sph}}(i)] / f_{\text{sph}}(i).$$

We then obtain the mass function of spheroids by

$$\frac{d^2N}{dV dM_{\text{sph}}} = \phi_{\text{sph}} \frac{dL_{\text{sph}}}{dM_{\text{sph}}}$$

and a black hole mass function $\Phi_{\text{BH}}$ is obtained using

$$\Phi_{\text{BH}} = \frac{d^2N}{dV dM_{\text{BH}}} = \left[ \frac{d^2N}{dV dM_{\text{sph}}} \right] d(M_{\text{BH}}|M_{\text{sph}}) dM_{\text{sph}},$$

where $P(M_{\text{BH}}|M_{\text{sph}})$ is the distribution of nuclear black hole masses given spheroid mass $M_{\text{sph}}$.

Some fraction $f_{\text{AGN}}$ of nuclear black holes are in an active (luminous) state and emit with luminosity $L_{\text{AGN}}$. Both $L_{\text{AGN}}$ and $f_{\text{AGN}}$ are likely to depend on $M_{\text{BH}}$. For simplicity we assume a functional relationship $L_{\text{AGN}} = F(M_{\text{BH}})$, although a distribution of luminosities $P(L_{\text{AGN}}|M_{\text{BH}})$ would be more realistic.

The AGN luminosity function $\phi_{\text{AGN}}$ is then

$$\phi_{\text{AGN}} = f_{\text{AGN}} \Phi_{\text{BH}} \frac{dM_{\text{BH}}}{dL_{\text{AGN}}}.$$ (1)

It is appropriate to formulate the ratio of $L_{\text{AGN}}$ to $M_{\text{BH}}$ in terms of the Eddington ratio $\epsilon$, the ratio of bolometric to Eddington luminosity $L_{\text{Edd}} = 1.3 \times 10^{38} (M_{\text{BH}}/M_\odot)$ erg s$^{-1}$,

$$\epsilon = \frac{L_{\text{AGN}}}{M_{\text{BH}} 1.3 \times 10^{38} \text{ erg s}^{-1}}.$$ (2)

### 3 CONSTRUCTING THE BLACK HOLE MASS FUNCTION

For the local galaxy luminosity functions we have chosen to use the recent determinations from the 2dF Galaxy Redshift Survey (Folkes et al. 1999). This provides Schechter function model luminosity functions for five different spectroscopic classes of galaxy (corresponding to different morphological types) at $z < 0.2$. We have used values for $f_{\text{sph}}$ (the fraction of $B$-band light arising from the spheroidal component) based on the values given by Meisels & Ostriker (1984).

The model luminosity functions and spheroid fractions are listed in Table 1. The model luminosity functions and spheroid fractions are listed in Table 1. For the spheroidal mass-to-light ratio we use the best-fitting relation of Magorrian et al. (1998) for $V$:

$$M_{\text{sph}}/M_\odot = 0.097 h(L/L_{\odot})^{1.18}$$

and assume $B - V = 0.9$ for the spheroidal component of all galaxy types (Pence 1976). For the black hole to spheroid mass distribution we use the best-fitting log–Gaussian relation from Magorrian et al. (1998):

$$P(M_{\text{BH}}|M_{\text{sph}}) = f_{\text{BH}} \exp\left[ -0.5 \log(M_{\text{BH}}/M_\odot) - \log(x_0) \right] \Delta / \sqrt{2\pi} \log_7(10),$$

where $\Delta = 0.51$, $f_{\text{BH}} = 0.97$ and $x_0 = 5.2 \times 10^{-3}$. We truncate this distribution at $\pm 3\sigma$ because otherwise it predicts an unrealistically large population of very massive ($>10^{11} M_\odot$) black holes.

The resultant black hole mass function is shown in Fig. 1.

### 4 FITTING THE ACCRETION RATE AND ACTIVE FRACTION

For the AGN luminosity function we have chosen to use the extended *Einstein* Medium Sensitivity Survey (EMSS) X-ray-selected sample (Stocke et al. 1991) restricted to type 1 (broad-line) Seyferts with $z < 0.2$. X-ray selection is ideal because it is insensitive to the properties of the optical host galaxy. The restriction to broad-line objects ensures that the sample contains only unobscured AGN for which the observed X-ray flux is a good measure of intrinsic luminosity, and the redshift restriction ensures that the sample is well matched to the 2dF galaxy sample and is without significant cosmological evolution.

The simplest relation between black hole mass and AGN luminosity is given by

$$L_{\text{AGN}} = \frac{M_{\text{BH}}}{M_\odot} \times 10^{38} \text{ erg s}^{-1}.$$ (1)

This relation is shown in Fig. 1. The resultant black hole mass function is shown in Fig. 1.

### Table 1. Schechter model galaxy luminosity functions from Folkes et al. (1999)

| Type  | $M_g^*$ | $\alpha$ | $\phi^*$ | $f_{\text{sph}}$ |
|-------|---------|----------|----------|-----------------|
| E/S0  | $-19.61$ | $-0.74$  | $9.0$    | $0.7$           |
| Sab   | $-19.68$ | $-0.86$  | $3.9$    | $0.25$          |
| Sbc   | $-19.38$ | $-0.99$  | $5.3$    | $0.15$          |
| Scd   | $-19.00$ | $-1.21$  | $6.5$    | $0.1$           |
| Sdm   | $-19.02$ | $-1.73$  | $2.1$    | $0.02$          |

Figure 1. Mass function of black holes derived in Section 3.
A very good fit to the X-ray luminosity function of type 1 AGN is easily found. The best fit has \( h = 1.8 \pm 0.5 \times 10^{-3} \) and \( f_{S1} = 7 \pm 2 \times 10^{-3} \) (where the errors define a box containing the 1σ, \( \Delta x^2 = 2.3 \), confidence interval) with an extremely low \( x^2 \) of 0.4 for six fitted data points and two free parameters (i.e. four degrees of freedom, so \( x^2/\nu = 0.1 \)). The best-fitting luminosity function is shown in Fig. 2(a); the predicted luminosity function passes almost exactly through the data. Fig. 2(b) shows \( \Delta x^2 \) confidence contours on the fitted parameters.

However, despite the very good fit, there is a problem with this simple model. It can be seen in Fig. 2(a) that the EMSS luminosity function is produced almost exclusively by E and S0 galaxies with only a small contribution from Sab galaxies at the low-luminosity end, but it is well known that Seyferts are often spirals. Indeed, spirals are a significant component of the EMSS Seyfert sample itself; this is demonstrated in Table 2 which gives the morphologies of the nearest EMSS Seyferts.

| Source     | log \( L_X \) | Morphology |
|------------|---------------|------------|
| MS1215.9+3005 | 2.18         | SB(s)a     |
| MS0339.8–2124 | 2.30         | SB(rs)a    |
| MS0459.5+0327 | 2.59         | E          |
| MS1158.6–0323 | 2.45         | E          |
| MS2252.2+1126 | 2.00         | Sab        |
| MS1846.5–7857 | 2.08         | SAB(r)b    |
| MS1136.5+3413 | 2.74         | SB0        |
| MS0048.8+2907 | 2.96         | SB(s)b     |

To reproduce the EMSS luminosity function with a mix of morphological types requires additional complexity in the model: to prevent early-type galaxies completely dominating the luminosity function, \( f_{S1} \) and/or \( e \) must depend on \( M_{BH} \) and/or galaxy morphology. Since different galaxy morphologies dominate the mass function at different masses, a direct dependency of \( f_{S1} \) or \( e \) on \( M_{BH} \) results in an indirect dependency on morphology and vice versa. If \( e \) is to be varied it must be in such a way as to steepen the model luminosity function so that the relative contribution of E/S0 galaxies is reduced in the EMSS luminosity range. This means that more massive black holes (in E/S0 galaxies) must accrete with lower Eddington ratios than those of lower mass. If \( f_{S1} \) is to be varied it must be such that a smaller proportion of more massive black holes are actively accreting Seyferts than those of lower mass.
An ad hoc example of one of these models is shown in Fig. 3(a). In this model (hereafter Model B) we have assumed that the fraction of active Seyferts in E/S0 galaxies, and their Eddington ratios, are only half that in other types, and the Seyfert 1 nuclei hosted by E and S0 galaxies accrete with only half the Eddington ratio of Seyfert nuclei in later galaxy types (Model B). The best-fitting luminosity function is an extremely good fit with a $\chi^2$ of 0.45, but this time the AGN luminosity function is produced by AGN with a more plausible mix of host galaxy morphologies. The fitted parameters are $f_{S1} = 7 \pm 3 \times 10^{-3}$ and $h \epsilon = 5 \pm 2 \times 10^{-3}$ for Sab and later galaxies (and by design half these values for E and S0 galaxies).

To obtain a conservative limit on the range of parameter space that brackets $f_{S1}$ and $\epsilon$, we have also considered the opposite extreme to the E/S0-dominated Model A: in Model C the active fraction of E and S0 galaxies is set to zero and they therefore make no contribution whatsoever to the AGN luminosity function. Since the fraction of Seyfert nuclei that are hosted by E and S0 galaxies is certainly between 0 and 1, it is reasonable to expect that the real values of $f_{S1}$ and $\epsilon$ must lie somewhere between the acceptable values for Models A and C. The best-fitting AGN luminosity function and $\Delta \chi^2$ confidence contours for Model C are shown in Fig. 4.

Figure 3. (a) X-ray luminosity function of the EMSS $z < 0.2$ AGN and best-fitting model in which the Seyfert 1 fraction of E and S0 galaxies is only half that in other types, and the Seyfert 1 nuclei hosted by E and S0 galaxies accrete with only half the Eddington ratio of Seyfert nuclei in later galaxy types (Model B). (b) $\chi^2$ confidence contours for the values of Eddington ratio $\epsilon$ and Seyfert 1 fraction $f_{S1}$ for Sab and later-type galaxies in Model B.

Figure 4. (a) X-ray luminosity function of the EMSS $z < 0.2$ AGN and best-fitting model in which E and S0 galaxies host no AGN (Model C). (b) $\chi^2$ confidence contours for the values of Eddington ratio $\epsilon$ and Seyfert 1 fraction $f_{S1}$ for Sab and later-type galaxies in Model C.
5 DISCUSSION

The approach used here easily reproduces the shape of the AGN luminosity function; models A, B and C all have extremely low χ². The steepening of the AGN luminosity function from low to high luminosity is inherited from the black hole mass function, which in turn inherits the shape from the galaxy luminosity functions. Hence the shape of the AGN luminosity function ultimately derives from the same physical processes that give rise to the shapes of galaxy luminosity functions.

The fitted Seyfert 1 fraction in Sab and later-type galaxies for Model B is ~ 0.5–1 per cent. This is quite a robust result: it is not strongly affected by the contribution of E and S0 galaxies because Models A and C have very similar best-fitting values for fS1. This compares well with the findings of optical emission-line surveys of local galaxies. Maiolino & Rieke (1995), find that 5 per cent of the revised Shapley–Ames catalogue of galaxies are Seyferts (with a Seyfert 1:Seyfert 2 ratio of 1:4 this corresponds to a Seyfert 1 fraction of 1 per cent). Ho, Filippenko & Sargent (1997), find a Seyfert fraction which is twice that found by Maiolino & Rieke (1995), and therefore (assuming the Maiolino & Rieke Seyfert 1:Seyfert 2 ratio) about a factor of 2 higher than would be expected from our value of fS1. However, their Seyfert detection rate is high because their survey is sensitive to objects with very weak emission lines, which they term ‘dwarf’ Seyferts; it is not yet known whether these objects have the same X-ray properties as more luminous Seyferts that make up the EMSS sample. Both Maiolino & Rieke (1995) and Ho et al. (1997) find that the most common morphology for Seyfert galaxies is Sa–Sb, further justifying our rejection of model A in Section 4.

In contrast to fS1, the value of ε for typical Sab Seyfert galaxies depends quite strongly on the Seyfert activity in E and S0 galaxies. Taking the extremes of models A and C, a conservative conclusion is that 0.001 < ε < 0.02 for Seyfert nuclei in Sab galaxies. Our reasonable model B suggests ε ~ 0.005 should be typical, considerably sub-Eddington and consistent with Seyfert activity occurring recurrently in a significant fraction of galaxies (model ‘R’ from Cavaliere & Padovani 1988). This is in good agreement with the predictions of recent models in which AGN, with lifetimes of the order of 10⁷ yr, are produced during the formation and merging of galaxies in a cold dark matter dominated Universe: Kauffmann & Haehnelt (2000) predict typical ε ~ 0.01, while Haiman & Menou (2000) predict typical ε ~ 0.001. Our results are also consistent with the range of Seyfert Eddington ratios given in the recent compilation by Wandel (1999). These lie between 0.001 and 1 and were obtained using a variety of different methods: broad-line region kinematics, X-ray variability and modelling accretion disc spectra.

However, the range of acceptable ε is too low to be consistent with accretion disc models that have large outbursts. Siemiginowska & Elvis (1997) show that if AGN accretion discs are subject to the thermal–viscous instability driven by hydrogen ionization (Lin & Shields 1986) they are probably only observed in outburst, with typical ε ~ 0.1. The study by Burderi, King & Szuszkiewicz (1998) concludes that if AGN have optically thick, geometrically thin accretion discs (Shakura & Sunyaev 1973) they almost certainly are subject to this kind of instability. The results presented here would therefore suggest that AGN are not fuelled by standard thin discs.

As explained in Section 4, the only way to obtain a plausible distribution of Seyfert host galaxies is to model the more massive black holes in early-type galaxies with smaller values of ε, fS1 or both. Both these alternatives have important consequences for our understanding of AGN behaviour.

The first (ε smaller for more massive AGN) is intuitively reasonable because the early-type galaxies that host more massive AGN contain less gas with which to feed them. However, it is contrary to the results of Wandel & Petrosian (1988) and Sun & Malkan (1989), who find from accretion disc modelling that luminous quasi-stellar objects (QSOs) are both more massive, and accrete with higher Eddington ratios, than Seyfert galaxies (although this could be interpreted as a dependence of Eddington ratio on redshift rather than mass). The AGN evolution models of Kauffmann & Haehnelt (2000) and Salucci et al. (1999), also favour a situation in which the more luminous present epoch AGN are more massive and have higher Eddington ratios.

The second way to obtain reasonable Seyfert morphologies, by modelling a smaller Seyfert fraction fS1 for more massive black holes, is less controversial. For example, both Maiolino & Rieke (1995) and Ho et al. (1997) find that a higher fraction of Sa–Sb galaxies have Seyfert nuclei than E/S0 galaxies. In this case the mass function of active nuclei must be steeper than the mass function of inactive nuclei, unlike the simple recurrent activity models represented by model ‘R’ in fig. 1 of Cavaliere & Padovani (1988).

This investigation can be substantially improved upon with a sample of X-ray-selected Seyferts with optical morphologies; this would allow the matching of galaxy and AGN luminosity functions individually for each morphological type, providing a much more rigorous solution than our model B. This obviously requires a larger AGN sample than the EMSS one used here, for which the luminosity functions of different morphological types would be dominated by Poisson noise. We can expect that such a sample may soon be available from ROSAT All Sky Survey optical identification programmes.

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REFERENCES

Boyle B. J., Shanks T., Peterson B. A., 1988, MNRAS, 235, 935
Burderi L., King A. R., Szuszkiewicz E., 1998, ApJ, 509, 85
Cattaneo A., Haehnelt M. G., Rees M. J., 1999, MNRAS, 308, 77
Cavaliere A., Padovani P., 1988, ApJ, 333, L33
de Vaucouleurs G., 1959, in Flügge S., ed., Handbuch der Physik, Vol. 53, Springer, Berlin, p. 275
Dunlop J. S., Peacock J. A., 1990, MNRAS, 247, 19
Elvis M. et al., 1994, ApJS, 95, 1
Fabian A. C., 1999, MNRAS, 308, L39
Folkes S. et al., 1999, MNRAS, 308, 459
Haehnelt M. G., Rees M. J., 1993, MNRAS, 263, 168
Haiman Z., Menou K., 2000, ApJ, 531, 42
Ho L., Filippenko A. V., Sargent W. L. W., 1997, ApJ, 487, 568
Kauffmann G., Haehnelt M., 2000, MNRAS, 311, 576
Kormendy J., Richstone D., 1995, ARA&A, 33, 581
Lin D. N. C., Shields G. A., 1986, ApJ, 305, 28
Lynden-Bell D., 1969, Nat, 223, 690
Magorrian J. et al., 1998, AJ, 115, 2285
Meisels A., Ostriker J. P., 1984, AJ, 89, 1451
Maiolino R., Rieke G. H., 1995, ApJ, 454, 95
Monaco P., Salucci P., Danese L., 2000, MNRAS, 311, 279
