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AGN have underweight black holes and reach Eddington

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ABSTRACT

Eddington outflows probably regulate the growth of supermassive black holes (SMBHs) in active galactic nucleus (AGN). I show that effect of the Rayleigh–Taylor instability on these outflows means that SMBH masses are likely to be a factor of a few below the $M-\sigma$ relation in AGN. This agrees with the suggestion by Batcheldor that the $M-\sigma$ relation defines an upper limit to the black hole mass. I further argue that observed AGN black holes must spend much of their lives accreting at the Eddington rate. This is already suggested by the low observed AGN fraction among all galaxies despite the need to grow to the masses required by the Soltan relation and is reinforced by the suggested low SMBH masses. Most importantly, this is the simplest explanation of the recent discovery by Tombesi et al. of the widespread incidence of massive ultrafast X-ray outflows in a large sample of AGN.

Key words: accretion, accretion discs – black hole physics – galaxies: active – galaxies: formation.

1 INTRODUCTION

It is now well established that the centre of almost every galaxy contains a supermassive black hole (SMBH), and that in many cases the mass of this hole is closely connected with properties of the host galaxy bulge through the $M-\sigma$ and $M-M_{bulge}$ relations (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Häring & Rix 2004). The connection is physically reasonable since the black hole binding energy ηMc^2 considerably exceeds the bulge binding energy $\sim M_{\rm bulge}\sigma^2$ (King 2003) (here $\eta \sim 0.1$ is the accretion efficiency and σ the velocity dispersion of the bulge). The black hole communicates its presence to the host by driving powerful outflows when it is fed matter at super-Eddington rates. If these outflows are momentum driven, i.e. communicate only their ram pressure to the surrounding interstellar gas, the $M-\sigma$ relation emerges naturally as specifying the black hole mass at which an Eddington outflow can drive a significant bubble into the bulge gas (King 2003, 2005). At smaller masses, the black hole can only drive bubbles which recollapse, and evidently do not interrupt the gas supply to the black hole which ultimately powers its growth.

This argument implicitly suggests that the $M-\sigma$ relation is an upper limit to the black hole mass, rather than a tight relation. It is now clear (Batcheldor 2010) that this is probably so, as observational selection makes it difficult to measure black hole masses below the relation (cf. Section 3).

The obvious question then is how far below this limit the majority of SMBHs lie. New insight into this question comes from recent X-ray observations by Tombesi et al. (2010a,b) of fast ($v \sim 0.1c$) outflows in a large fraction of local active galactic nuclei (AGN). I shall argue here that this means that most local AGN contain black holes lying below the $M-\sigma$ limit, and that most of these systems undergo super-Eddington episodes which switch off only for relatively short intervals. The hole masses are probably not very far below the $M-\sigma$ value. I will show that Eddington outflows at masses significantly below this are Rayleigh–Taylor unstable and therefore inefficient in suppressing accretion.

2 BLACK HOLE GROWTH

The argument by Soltan (1982) relates the mass density of black holes in the local Universe to the total background radiation they produced while growing. It suggests that the average medium to large galaxy hosts a black hole of mass $\gtrsim 10^8 \text{ M}_{\odot}$. It is reasonable to suppose that the growth phases of these SMBH are observable as AGN. But since the incidence of AGN among all galaxies is relatively low, this must mean that the holes spend much of their time growing at the maximum possible rate, i.e. that specified by the Eddington limit. In this case the $M-\sigma$ relation constrains their growth, and we should expect the black hole masses in AGN to lie *below* the relation, with a galaxy nucleus ceasing to be active once its SMBH reaches this mass. We are thus led to the conclusions that

(a) AGN must radiate at *close* to the Eddington luminosity for much of their lives;

(b) their black holes must be *underweight*, i.e. below the $M-\sigma$ relation.

Although these conclusions follow from accepting that the observed AGN do represent the growth phases of SMBH, neither of them is widely adopted in practice. This amounts either to simply

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ignoring the argument, or to tacitly assuming that SMBH growth only happens in AGN which are somehow unobservable. I shall argue below that this tacit assumption cannot be correct.

3 M-σ AS AN UPPER MASS LIMIT

A major reason for the reluctance in accepting conclusion (b) above has probably been the tightness of the observed $M-\sigma$ relation. However, Batcheldor (2010) has recently pointed out that the SMBH masses populating the observed $M-\sigma$ relation are found by using the velocities of stars within the SMBH sphere of influence

$$R_{\rm inf} = \frac{2GM}{\sigma^2}.$$
 (1)

Since one must resolve R_{inf} in order to get an unambiguous dynamical mass estimate, measured values of M correlate with σ . Batcheldor (2010) shows that it is unlikely that one can measure masses M significantly below the value given by the observed $M-\sigma$ relation. Accordingly we are at liberty to regard the observed relation as an upper limit on the SMBH mass for a given σ .

4 SMBH FEEDBACK AND THE *M*-σ RELATION

We have inferred that SMBH grow at the Eddington rate during active phases. The resulting massive outflows are observed (see Section 5). They offer a natural way of communicating some of the hole's binding energy to the host galaxy, and thus establishing the $M-\sigma$ relation as they shock against the host interstellar medium (ISM). Whatever the Eddington ratio $\dot{m} = \dot{M}/\dot{M}_{Edd}$, the accretion luminosity is always $\sim L_{Edd}$, because radiation pressure expels excess accretion at each radius to ensure that the local Eddington limit is not exceeded. Shakura & Sunyaev (1973) show for example that in a disc geometry the luminosity limit is of order $L_{Edd}(1+\ln \dot{m})$, where L_{Edd} is the standard expression for the spherical Eddington limit. As the outflow results from radiation driving, there are two extreme possibilities (cf. King 2003, 2005, 2010).

For $\dot{m} \sim 1$ most photons in the AGN radiation field scatter about once and transmit their total momentum $L_{\rm Edd}/c$ to the outflow. Further, the outflow shocks against the host ISM are effectively cooled by Compton cooling from the AGN radiation field. Thus only the outflow ram pressure $L_{\rm Edd}/c$ is communicated to the host: this is a momentum-driven outflow. The outflow sweeps up the host ISM in a shell, and solving the shell's equation of motion shows that this recollapses unless the SMBH mass has reached the critical value

$$M_{\sigma}(\text{mom}) = \frac{f_{g}\kappa}{\pi G^{2}}\sigma^{4}$$
⁽²⁾

(where $f_g \simeq 0.16$ is the cosmic baryon fraction with respect to dark matter). If the hole mass is $\ge M_{\sigma}$ the shell can reach significant radii within the host and presumably suppress central accretion and SMBH growth. A simple way of deducing this result is to equate the thrust $L_{\rm Edd}/c$ to the weight of the swept-up gas shell. For an isothermal density distribution the weight of a swept-up gas shell turns out to be $W = 2f_{\rm g}\sigma^4/G$, independent of radius *R* [the swept-up mass goes as *R*, while its gravity $\sim GM(R)/R^2$ goes as 1/R – see King 2010]. Hence setting $L_{\rm Edd} \simeq W$ gives an estimate of the mass. (The solution of the shell's equation of motion shows that the radiation thrust accelerates the outflow to a fixed terminal speed, justifying the approximation; cf. King 2005.)

At the opposite extreme, for $\dot{m} \gg 1$, multiple scattering within the outflow means that almost all the total photon energy is given to the outflow. The outflow shock against the ISM is now not effectively

cooled, and the total energy rate L_{Edd} now does *P* d *V* work against the weight of the swept-up interstellar gas. This is an energy-driven outflow, as originally considered by Silk & Rees (1998). Equating the energy injection rate L_{Edd} to the rate of working $W\sigma$ as the shell begins to move to large radii we find

$$M_{\sigma}(\mathrm{en}) \simeq \frac{f_{\mathrm{g}}\kappa}{\pi G^2 c} \sigma^5.$$
 (3)

Relations (2) and (3) have no free parameter. Each is potentially self-consistent: the accretion rate is likely to be close to Eddington for the high-mass momentum-driven sequence (i.e. $\dot{m} \simeq 1$) and significantly super-Eddington for the low-mass energy-driven sequence (i.e. $\dot{m} \gg 1$) (cf. King 2010). The momentum-driven value M_{σ} (mom) is very close to the observed relation

$$M \simeq 2 \times 10^8 \,\mathrm{M_{\odot}} \sigma_{200}^4 \tag{4}$$

(Ferrarese & Merritt 2000; Gebhardt et al. 2000).

In contrast, relation (3) is a factor of $\sim \sigma/c \sim 10^{-3}$ below the observed one, and would imply unobservably small hole masses. It is important to understand why this low-mass sequence is apparently disfavoured, as if not, it would constitute a bottleneck to SMBH growth, and make it hard to understand why SMBHs apparently do reach the higher mass sequence (2).

The reason why the energy-driven sequence does not seem to occur in nature appears to be that the very strong density contrast between the shocked wind and the host ISM in the energy-driven case causes the bubble blown by the outflow to break up through the Rayleigh–Taylor instability. By contrast, in a momentum-driven outflow the post-shock density is far higher, making the corresponding bubble Rayleigh–Taylor stable for masses near M_{σ} , and potentially able to cut off accretion. In this latter case, the speed v of the pre-shock outflow is given by the condition

$$\dot{M}v = \frac{L_{\rm Edd}}{c} = \eta \dot{M}_{\rm Edd}c \tag{5}$$

as

$$v = \frac{\eta}{\dot{m}}c.$$
 (6)

The continuity equation gives the pre-shock density as

$$\rho = \frac{\dot{M}}{4\pi b R^2 v} = \frac{\dot{m}^2 \dot{M}_{\rm Edd}}{4\pi R^2 b \eta c} \tag{7}$$

at radius *R*, where *b* is the fractional solid angle of the outflow (we shall see later that *b* is of the order of unity). As the outflow shock is efficiently cooled, the density is strongly increased [by a factor of $\sim (v/\sigma)^2$] there. Thus the outflow density in contact with the host ISM is

$$\rho_m \simeq \frac{\eta \dot{m}^4 \dot{M}_{\rm Edd} c}{4\pi R^2 b \sigma^2}.$$
(8)

The ISM density is roughly the isothermal value

$$\rho_{\rm ISM} = \frac{f_{\rm g}\sigma^2}{2\pi R^2 G},\tag{9}$$

so combining we find

$$\frac{\rho_{\rm ISM}}{\rho_m} \simeq \frac{b}{2\dot{m}^4} \frac{M_\sigma(\rm mom)}{M}.$$
(10)

Thus the bubble is Rayleigh–Taylor stable, and can propagate outwards and suppress accretion provided that

$$M \gtrsim \frac{b}{2\dot{m}^4} M_{\sigma}(\mathrm{mom}).$$
 (11)

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Since $b \sim \dot{m} \sim 1$, we see that central accretion and SMBH growth is likely to be suppressed for $M \sim M_{\sigma}$ (mom). (Note that accretion of gas within the black hole sphere of influence can continue for a time after the outflow bubble begins to propagate to significant radii.) This suggests that SMBH masses in AGN are likely to be only a factor of a few below the $M-\sigma$ limit (2), as they can grow only when the externally imposed accretion rate is not far above the Eddington value and so potentially spend longer at such masses.

For an energy-driven outflow, the pre-shock outflow velocity follows from

$$\frac{1}{2}\dot{M}v^2 = L_{\rm Edd} = \eta \dot{M}_{\rm Edd}c^2 \tag{12}$$
as

$$v = \left(\frac{2\eta}{\dot{m}}\right)^{1/2}.$$
(13)

With this change, and compression only by a factor of 4 in the outflow shock (since cooling is negligible), the SMBH growth suppression condition corresponding to (11) becomes

$$M > \frac{b}{2\dot{m}^{3/2}} \left(\frac{c}{\sigma}\right)^3 M_{\sigma}(\text{en}) \sim 10^9 \frac{b}{\dot{m}^{3/2}} M_{\sigma}(\text{en}),$$
(14)

which is clearly impossible to satisfy for realistic parameters. Thus an energy-driven bubble is never Rayleigh–Taylor stable and cannot halt SMBH growth. We conclude that SMBH growth is not halted at the energy-driven sequence (3), and given an adequate mass supply can continue all the way to the momentum-driven limit (2).

5 OBSERVED OUTFLOWS

We have seen that SMBH feedback occurs through massive outflows carrying the Eddington momentum. These outflows must have speeds $v \simeq 0.1c$ (cf. equation 6). Moreover since the momentum outflow rate is specified by the quantity $\rho R^2 v$ (cf. equation 7), the ionization parameter

$$\xi = \frac{L_{\rm i}}{NR^2} \simeq \frac{l_{\rm i} L_{\rm Edd} m_{\rm p}}{\rho R^2} \tag{15}$$

is also specified (here $L_i = l_i L_{Edd}$ is the ionizing luminosity of the AGN, with l_i given by the spectral shape and ionization threshold). King (2010) shows that this condition requires that the outflows should have ionization parameters

$$\xi = 3 \times 10^4 \eta_{0.1}^2 l_2 \dot{m}^{-2},\tag{16}$$

where $l_2 = l_i/10^{-2}$ and $\eta_{0.1} = \eta/0.1$, and thus show lines in the X-ray region of the spectrum. This is indeed what is observed (Pounds et al. 2003a,b; O'Brien et al. 2005). This reasoning shows that any *outflow* with velocities ~ 0.1*c* seen in X-ray lines *carries* mass and momentum rates of order \dot{M}_{Edd} , L_{Edd}/c .

The papers by Tombesi et al. (2010a,b) show that outflows with these properties are extremely common. They are detected in a significant fraction (>35 per cent) of a sample of more than 50 local AGN. This must mean first that the solid angle factor *b* cannot be small (Tombesi et al. deduce $b \gtrsim 0.6$) and secondly, that a large number of local AGN have undergone or continue to undergo episodes of Eddington accretion.

We get more information from the hydrogen column densities, which are observed to lie in the range 10^{22} cm⁻² < $N_{\rm H}$ < 10^{24} cm⁻². Using equation (7) we find

$$N_{\rm H} = \int_{R_{\rm in}}^{\infty} \frac{\rho}{m_{\rm p}} \mathrm{d}R = \frac{\dot{m}^2 \dot{M}_{\rm Edd}}{4\pi b \eta c m_{\rm p} R_{\rm in}} \simeq \frac{3 \times 10^{37} \dot{m}^3 M_8}{b \eta_{0.1}^2 R_{\rm in}} \,\mathrm{cm}^{-2},$$
(17)

where $R_{\rm in}$ is the inner radius of the flow. For a continuing outflow this would be of the order of 100 Schwarzschild radii (corresponding to the escape speed ~0.1*c*). It is difficult to detect the corresponding very high column densities ~10²⁴ cm⁻² as the gas is likely to be fully ionized. The highest observed columns presumably correspond to continuing steady outflows which have recombined at some distance from the black hole. Lower columns may reveal cases where the outflow is episodic, and last stopped at a time $t_{\rm off}$ before the observation. In this case $R_{\rm in}$ takes a larger value $\simeq vt_{\rm off}$. Using (17) we get

$$t_{\rm off} = 0.2 \frac{\dot{m}^3 M_8}{b \eta_{0.1}^2 N_{23}} \,\rm{yr},\tag{18}$$

where $M_8 = M/10^8 \,\mathrm{M_{\odot}}$, $N_{23} = N_{\mathrm{H}}/(10^{23} \,\mathrm{cm^{-2}})$. Thus even the lowest observed columns ($\sim 10^{22} \,\mathrm{cm^{-2}}$) correspond to outflows which switched off only 2 yr ago. This suggests that outflows are even more common than one might expect from the simplest interpretation of the results of Tombesi et al. (2010a,b).

5.1 Eddington or not?

Tombesi et al. (2010b) consider three sources in detail (3C 111, 3C 120, 3C 390.3) and suggest that their luminosities are below L_{Edd} . However, this procedure uses black hole masses based on assumption that either the $M-\sigma$ relation, or the SMBH-bulge mass relation, holds for all SMBHs, at least in a statistical sense. [The $M-\sigma$ relation is used to calibrate the reverberation masses for 3C 120, 3C 390.3 (Peterson et al. 2004) and the SMBH mass for 3C 111 uses the stellar bulge luminosity (Marchesini, Celotti & Ferrarese 2004).] We have seen that both relations are likely to give overestimates of the SMBH mass, and hence overestimates of L_{Edd} . Fig. 16 of Peterson et al. (2004) shows that a reduction by a factor of \sim 3 of SMBH masses estimated in this way would put most of the sample of 35 reverberation-mapped AGN close to their Eddington luminosities. In addition to this, estimating whether an AGN is near L_{Edd} requires us to know not only its SMBH mass, but also its true bolometric luminosity L_{bol} , both to high accuracy. The latter problem is unlikely to be easier than the former.

6 CONCLUSIONS

This Letter has argued that the black hole mass is a factor of a few below the $M-\sigma$ mass in active galaxies, and that a large fraction of AGN are fed mass at a super-Eddington rate, accreting just the Eddington value and expelling the excess.

The first point follows from noting that SMBH growth towards the momentum-driven limit (2) is inevitable given a sufficient mass supply. In particular, energy-driven outflows are Rayleigh–Taylor unstable, so the mass is not constrained by the energy-driven limit (3). Growth only slows when momentum-driven outflows become Rayleigh–Taylor stable, i.e. when the black hole is a factor of a few below the $M-\sigma$ value. So SMBH masses in AGN are likely to be below, but fairly close to, this critical value. This agrees with the suggestion by Batcheldor (2010) that the $M-\sigma$ relation is an upper limit to SMBH masses.

The idea that AGN regularly reach L_{Edd} follows naturally from noting that SMBH have to grow rapidly to reach the masses specified by the Soltan relation. It is consistent with the first proposition above (low SMBH masses): Eddington ratios for observed AGN must be higher than previously estimated if their black holes lie below the $M-\sigma$ relation rather than on it, as is sometimes assumed.

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The strongest evidence for Eddington accretion comes from the papers by Tombesi et al. (2010a,b), which show that a large fraction of nearby AGN have outflow with velocities $\sim 0.1c$ and ionization parameters $\xi \sim 10^4 - 10^5$, as expected. At face value this suggests that a large fraction of local AGN are fed at super-Eddington rates, and I have argued that it is difficult to avoid this conclusion.

After this paper was accepted for publication my attention was drawn to the paper by Bluck et al. (2010). This reaches very similar conclusions from an observational approach.

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