Fuelling Active Galactic Nuclei

A. R. King\textsuperscript{1} and J.E. Pringle\textsuperscript{1,2}

\textsuperscript{1}Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH
\textsuperscript{2}Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

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ABSTRACT

We suggest that most nearby active galactic nuclei are fed by a series of small–scale, randomly–oriented accretion events. Outside a certain radius these events promote rapid star formation, while within it they fuel the supermassive black hole. We show that the events have a characteristic time evolution. This picture agrees with several observational facts. The expected luminosity function is broadly in agreement with that observed for moderate–mass black holes. The spin of the black hole is low, and aligns with the inner disc in each individual feeding event. This implies radio jets aligned with the axis of the obscuring torus, and uncorrelated with the large–scale structure of the host galaxy. The ring of young stars observed about the Galactic Centre are close to where our picture predicts that star formation should occur.

Key words: accretion, accretion discs – black holes, galaxies – active

1 INTRODUCTION

It is now generally accepted that the nuclei of most galaxies contain supermassive black holes. Assembling the observed hole masses by accretion at plausible efficiency accounts for the emission of active galactic nuclei (AGN) over cosmic time (Soltan, 1982; Yu & Tremaine, 2002). This implies that essentially every galaxy is intermittently active, in phases when its black hole grows. Only a small fraction of galaxies are observed to be active (e.g. Heckman et al., 2004), so we know that these phases are short.

Yet we still do not understand how gas gets down to the black hole. There are a number of candidates, including galaxy mergers (major and minor), bars, bars within bars, turbulence in the ISM, stellar mass loss, and viscous accretion discs. However, the nature of the problem is often underestimated. For example, in a recent review article, Wada (2004) discusses ‘Fuelling Gas to the Central Region of Galaxies’ in terms of bringing gas inwards to around 100 pc from the central black hole. But, as emphasised by Shlosman, Begelman & Frank (1990), the gas must get to remarkably small radii before the inner viscous accretion disc can take over and bring the gas to the hole within the observed activity timescale. The inflow timescale through a disc of size 1 pc is already \(\sim 10^9\) yr, even with maximal assumptions about viscosity. For shorter AGN phases, or less efficient viscosity, the gas must be fed to the central disc at still smaller radii.

Observations show a wide range of activity, from highly luminous quasars at redshifts up to \(z \simeq 6\), through the barely detectable nuclei in LINERS, to the weak activity of our own Galactic Centre. It seems likely that all of the fuelling processes discussed so far may play a role in at least some galaxies. In this paper we focus attention on the fuelling of the nucleus in a normal Seyfert galaxy, with a central black hole of mass \(M \sim 10^7 - 10^8\) M\(_\odot\). (Ferrarese et al., 2001; Heckman et al., 2004; Denney et al., 2006) and luminosity \(L \sim 0.1L_E\) (with \(L_E\) the Eddington luminosity) thus accreting at a rate \(M \sim 0.2M_\odot\) yr\(^{-1}\). In a typical Seyfert event lasting, say, \(10^6\) yr, this would imply an accreted mass \(\Delta M \sim 2 \times 10^5\) M\(_\odot\) (e.g. Emsellem, 2002, 2004; Martini, 2004). This is ridiculously small compared with the gas available in a typical spiral galaxy, and we immediately see that we are not concerned with major gas flows involving spiral arms or galactic bars. Feeding the black hole at such modest rates needs only some small–scale event to drop a little material of low angular momentum into the central regions of the galaxy.

We have two pieces of evidence suggesting what such an event might be. First, Kinney et al. (2000; see also Nagar & Wilson, 1999) found that in a sample of nearby \((z \leq 0.031)\) Seyfert galaxies, the direction of the jet from the central black hole, and therefore presumably the orientation of the central regions of the accretion disc, were unrelated to the orientation of the disc of the host galaxy. Second, Schmitt et al (2003) surveyed extended [O III] emission in a sample of nearby Seyfert galaxies, and found that although the [O III] emission is well aligned with the radio, there is no correlation between its orientation and the major axis of the host galaxy. Assuming that the orientation of the [O III] emission is governed by the geometry of the inner torus, of typical radius 0.1 – 1.0 pc (e.g. Antonucci, 1993), this means...
that the central disc flow has angular momentum unrelated to that of most of the gas in the host galaxy.

This tells us two things (see also the discussion in Kinney et al., 2000). First, in line with our inference above, if the galactic disc supplied the torus material via bar–driven disc evolution, or grand–design nuclear spirals, or similar mechanisms, some means of randomising its rotation axis in the central regions is needed. For without some such mechanism we expect such processes to leave evidence of the angular momentum of the galactic disc, which is not seen. There is currently no suggestion as to what this mechanism might be, although one can appeal to the fact that the galactic disc is much thicker than the radial scale of a few parsecs that we are interested in. In the absence of a randomising mechanism the gas must come from outside the galaxy as part of a succession of (very) minor mergers. Where in a galaxy a very small merging satellite deposits its gas is not straightforward to compute (Velasquez & White, 1999; Taylor & Babul, 2001). Kendall, Magorrian & Pringle (2003) find that if such small merging satellites are to deposit gas near the nucleus then their initial orbits must be fairly accurate shots. Kendall et al. (2003) also conclude that such small merging satellites which do manage to reach the nucleus arrive there on more or less randomly oriented orbits.

Second, the inner disc (specifying the radio jet axis) remains aligned with the torus. In an earlier paper (King & Pringle, 2006, Section 3) we showed that repeated small–scale fuelling has precisely this effect. It causes counteralignment of the hole (King et al., 2005) in about one–half of all accretion events, and thus spindown, which is more efficient than spinup. Once the hole’s mass has doubled, its angular momentum is always smaller in magnitude than that of any accretion event. It then always aligns its spin with the inner disc and thus the torus.

Thus we have argued that the fuelling of low luminosity AGN proceeds via a series of randomly oriented, small–scale accretion events, acting directly in the region of the central black hole. The material deposited in such an event is likely to settle quickly into a ring or disc of material within a few local dynamical (or orbital) timescales \( t_{\text{dyn}} \), where

\[
t_{\text{dyn}} = 2.9 \times 10^2 \left( \frac{M}{10^8 M_\odot} \right)^{-1/2} \left( \frac{R}{0.1 \text{pc}} \right)^{3/2} \text{ yr}.
\]  

(1)

It is well known that such a disc is likely to be self–gravitating outside some radius \( R_{\text{sg}} \sim 0.01 – 0.1 \) pc (Shlosman et al., 1990; Collin–Souffrin & Dumont, 1990, Hure et al., 1994). Further, in the outer regions of these discs the cooling timescales are sufficiently short that self–gravity is likely to cause star formation, rather than enhanced angular momentum transport (Shlosman & Begelman, 1989; Collin & Zahn, 1999). For the discs we consider in this paper, which are relatively thin (because of efficient cooling) and of low mass \( (M_{\text{disc}} \ll M_\text{hole}) \) self–gravity appears first in modes with azimuthal wavenumber \( m \approx R/H \), producing transient spiral waves which transport angular momentum (Anthony & Carlberg, 1988; Lodato & Rice, 2004, 2005). It is reasonable to suppose that where the disc is locally gravitationally unstable in this way, most of the gas forms stars.

We therefore propose the hypothesis that all, or at least most of, the gas initially at radii \( R > R_{\text{sg}} \) is either turned into stars, or expelled by those stars which do form, on a rapid (almost dynamical) timescale (see also Shlosman & Begelman, 1989). This corresponds to a nuclear starburst of the kind often associated with AGN (e.g. Scoville 2002). A starburst like this lasts around 3 \( \times 10^6 \) yr in terms of its ionising flux (O and early B stars). We suppose further that all the gas which is initially at radii \( R < R_{\text{sg}} \) forms a standard accretion disc, which slowly drains on to the black hole and powers the AGN. We stress that under the simple form of this hypothesis the nuclear starburst and the AGN are two different manifestations of the same accretion event, but do not feed on one another. We note that such a picture provides at least a qualitative explanation for the existence of the ring(s) of young stars seen around the black hole in the centre of the Milky Way (Genzel et al., 2003).

In Section 2, we investigate the properties of the accretion disc at radii \( R < R_{\text{sg}} \). In Section 3, we consider the time–dependence of such an event and in Section 4 present a simplified luminosity function under the assumption that all events are identical, but randomly timed.

### 2 PROPERTIES OF THE DISC

We use the steady disc properties derived by Collin–Souffrin & Dumont (1990) in the context of AGN, which are essentially the same as those derived by Shakura & Sunyaev (1973) for steady discs in the context of X–ray binaries. The disc surface density is given as

\[
\Sigma = 7.5 \times 10^6 \left( \frac{\alpha}{0.03} \right)^{-4/5} \left( \frac{\epsilon}{0.1} \right)^{-3/5} \left( \frac{L}{0.1 L_E} \right)^{3/5} M_8^{1/5} \left( \frac{R}{R_s} \right)^{-3/5} \text{ g cm}^{-2}.
\]  

(2)

Here \( \alpha \) is the standard Shakura & Sunyaev (1973) viscosity parameter, \( \epsilon \) is the accretion efficiency, so that the luminosity \( L \) and accretion rate \( \dot{M} \) are related by

\[
L = \epsilon \dot{M} c^2,
\]  

(3)

also

\[
L_E = 1.4 \times 10^{46} M_8 \text{ erg s}^{-1},
\]  

(4)

is the Eddington luminosity, \( M_8 \) is the black hole mass, \( \dot{M} \), in units of \( 10^8 M_\odot \), \( R \) is the radius and \( R_s = 2.96 \times 10^{13} M_8 \) cm

(5)

is the Schwarzschild radius of the central black hole.

Then the mass of the disc \( M(< R) \) interior to radius \( R \) is given by

\[
M(< R) = 2.94 \times 10^{34} \left( \frac{\alpha}{0.03} \right)^{-4/5} \left( \frac{\epsilon}{0.1} \right)^{-3/5} \left( \frac{L}{0.1 L_E} \right)^{3/5} M_8^{11/5} \left( \frac{R}{R_s} \right)^{7/5} \text{ g}.
\]  

(6)

The disc semi–thicknes \( H \) is given by

\[
H \sim \frac{1}{2} \left( \frac{L}{0.1 L_E} \right)^{1/5} M_8^{-1/10} \left( \frac{R}{R_s} \right)^{1/10} \text{ g}.
\]  

(7)

The condition for the disc to become self–gravitating is approximately (e.g. Pringle, 1981)
\[
\frac{M(<R)}{M} \geq \frac{H}{R}.
\]

This occurs at radii \( R \geq R_{\text{sg}} \), where
\[
\frac{R_{\text{sg}}}{R_*} = 1.13 \times 10^3 \left( \frac{\alpha}{0.03} \right)^{14/27} \left( \frac{\epsilon}{0.1} \right)^{8/27} \times \left( \frac{L}{0.1L_E} \right)^{-8/27} \frac{M_8}{M}^{26/27}.
\]

We note that this implies
\[
R_{\text{sg}} = 0.01 \left( \frac{\alpha}{0.03} \right)^{14/27} \left( \frac{\epsilon}{0.1} \right)^{8/27} \left( \frac{L}{0.1L_E} \right)^{-8/27} M_8^{1/27} \text{pc} \quad (10)
\]

almost independently of the black hole mass. This arises because (10) is an integrated form of the standard steady-state disc equation \( \dot{M} = 3\pi v\Sigma \) combined with (8), which we can express as
\[
R_{\text{sg}} \simeq \frac{3}{2} \frac{H}{R} c_s \frac{M}{M} \quad (11)
\]

where \( c_s \) is a mean sound speed and we note from (7) that \( H/R \simeq \) constant. Encouragingly, we see that \( R_{\text{sg}} \) is only slightly smaller than the inner edge \( R \simeq 0.03 \) pc of the ring of young stars seen around the black hole in the centre of the Milky Way (Genzel et al., 2003). This is to be expected, as the disc within \( R_{\text{sg}} \) must pass its angular momentum to the self-gravitating region further out which in our picture produces these stars.

The mass inside the radius \( R_{\text{sg}} \) is given by
\[
M_{\text{sg}} = 2.76 \times 10^5 \left( \frac{\alpha}{0.03} \right)^{-2/27} \left( \frac{\epsilon}{0.1} \right)^{-5/27} \times \left( \frac{L}{0.1L_E} \right)^{5/27} M_8^{23/27} M_\odot,
\]

which is of course just \((H/R)M\) with \( H/R \) evaluated at \( R_{\text{sg}} \) (cf. equation 4).

The accretion rate is given by \( \dot{M} = L/c^2 \), which implies
\[
\dot{M} = 0.245 \left( \frac{\epsilon}{0.1} \right)^{-1} \left( \frac{L}{0.1L_E} \right) M_8 M_\odot \text{yr}^{-1}. \quad (13)
\]

Then the evolution timescale of the disc is given by \( \tau_{\text{sg}} = M_{\text{sg}}/\dot{M} \), which gives
\[
\tau_{\text{sg}} = 1.12 \times 10^6 \left( \frac{\alpha}{0.03} \right)^{-2/27} \left( \frac{\epsilon}{0.1} \right)^{22/27} \times \left( \frac{L}{0.1L_E} \right)^{-22/27} M_8^{4/27} \text{yr}. \quad (14)
\]

Again we note that \( \tau_{\text{sg}} \sim (H/R)(M/\dot{M}) \).

### 3 PROPERTIES OF AN ACCRETION EVENT

In the previous Section we established the general properties of the non-self-gravitating disc, assuming that it was accreting steadily, and giving rise to a luminosity \( L \). Of course this is not precisely what we require for the present problem. What we are assuming is that the disc, of initial mass \( M_{\text{sg}} \), is deposited by the accretion event in some unknown configuration, and then evolves due to viscosity. As for most accretion discs it is fair to assume that initially most of the mass, and most of the angular momentum of the disc, is predominantly at large radius, and therefore at around \( R_{\text{sg}} \).

But whatever the initial configuration, within a timescale of

\[ t_{\text{ev}} \sim 3 \times 10^7 / \text{N yr} \quad (\text{Heckman et al.}, 2004). \]

at most \( \tau_{\text{sg}} \) given by eq. (14) the disc evolves to resemble a steady disc at radii \( R \leq R_{\text{sg}} \) (e.g. Pringle, 1981). Thus using the formulae derived in Section 2 gives a good approximation to the actual disc properties after a brief initial period. We can now use this to estimate the properties of the disc, and therefore of the AGN event, as it evolves.

From eqn. (2) we see that \( \Sigma \propto M^{3/5} R^{-3/5} \). For a steady disc we know (Pringle 1981) that \( M \propto \nu \Sigma \), where \( \nu \) is the viscosity. From these two relationships we can deduce that for these discs \( \nu \propto \Sigma^{2/3} R \). For such discs, similarity solutions (Pringle 1991) imply that at late times the accretion rate, and hence luminosity, varies with time as \( L \propto t^{-19/16} \). Thus we expect luminosity evolution roughly to follow
\[
L = L_{\text{init}} [1 + (t/\tau_{\text{sg}})]^{-19/16}. \quad (15)
\]

### 4 IMPLICATIONS FOR THE LUMINOSITY FUNCTION

Heckman et al. (2004) find that most of the current accretion on to black holes is on to those with masses in the range \( 10^7 - 10^8 M_\odot \). In addition they find that of low mass black holes, with masses \( M < 3 \times 10^7 M_\odot \), only 0.2 per cent are growing at a rate which accounts for 50 per cent of the fuelling. They point out that this implies that strong fuelling therefore only lasts for a time \( t_{\text{fuel}} \sim 0.002 \times t_H \), where \( t_H \sim 1.4 \times 10^{10} \) years is the age of the universe. Thus the total time during which strong fuelling is taking place is around \( t_{\text{fuel}} \sim 3 \times 10^7 \) years, or, if there are \( N \) fuelling events per black hole per Hubble time, it implies that each event lasts around \( t_{\text{ev}} \sim 3 \times 10^7 / N \text{ yr} \) (Heckman et al., 2004).

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**Figure 1.** Form of the AGN luminosity function predicted by the fuelling process, and subsequent disc evolution, discussed in this paper. The fraction \( F \), of those sources with luminosities less than \( L/L_E \) is shown as a function of \( L/L_E \). This is similar in form to those presented in Figure 3 of Heckman et al., 2004.
Accordingly we make some simplifying assumptions to work out the luminosity function we might expect from our model. We take $\alpha = 0.03$ and $\epsilon = 0.1$, and consider black holes with mass $10^7 M_\odot$ as representative of the range making the major contribution to the distribution of accreting black holes. We assume that these black holes undergo random, but identical, accretion events such that the initial luminosity of each event is $L_E$. In this case, we see from the above that the initial disc mass is $M_{\text{sd}} \approx 5.95 \times 10^4 M_\odot$, and the initial evolution timescale is $\tau_{\text{sd}} \approx 2.14 \times 10^4$ yr. Equating this timescale to the length of each event, $t_{\text{ev}}$, we see that the number of events has to be about $N = 0.002 t_H / \tau_{\text{sd}} \approx 116$, and therefore the average time between events is $t_{\text{ev}} \approx t_H / N = \tau_{\text{sd}} / 0.002 \approx 1.2 \times 10^8$ yr.

Writing $f = L / L_E$, our assumption implies that the initial value of $f$ is 1. The average final value is $\bar{f}_{\text{end}} = f_{\text{in}} / (1 + \lambda_{\text{end}})^{19/16}$, where $\lambda_{\text{end}} = t_{\text{rep}} / \tau_{\text{sd}} = 500$, and so the maximum possible range of $f$ is $(1 + \lambda_{\text{end}})^{19/16}$. Of course observations cannot probe this full range, and from Figure 3 of Heckman et al. (2004) we see that for $10^7 M_\odot$ black holes the observed range of $f$ is around 40 (corresponding to $\lambda \gtrsim 18$ and $N \lesssim t_H / 18 \tau_{\text{sd}} = 540$).

Inverting equation (15) we find that

$$\frac{t}{\tau_{\text{sd}}} = f^{-16/19} - 1,$$

for $0 < f \lesssim \tau_{\text{sd}}$. Then assuming that fuelling events for different black holes are independent, we find that the fraction $F(> f)$ of black holes with luminosities $> f$ is given by

$$F(> f) = \frac{f^{-16/19} - 1}{\bar{f}_{\text{end}}^{16/19} - 1}.$$

We plot this in Figure 1. As can be seen, this curve has a similar form to the distributions of low–mass black holes (3 $\times 10^6 M_\odot$ – 3 $\times 10^7 M_\odot$) in Figure 3 (Left) of Heckman et al. (2004) in the observed range $1 \lesssim f \lesssim 40$. Given the simplicity of our assumptions (identical independent fuelling events etc) we regard this as encouraging.

5 CONCLUSIONS

We have suggested that the feeding of most nearby active galactic nuclei proceeds via a series of small–scale, randomly–oriented accretion events, rather than large–scale events bearing the imprint of the host galaxy. Outside a certain radius these events cause rapid star formation, while within it they feed the supermassive black hole. This picture implies a characteristic time decay of each event and implies a luminosity function broadly in agreement with that observed for moderate–mass black holes. The chaotic nature of the accretion keeps the black hole spin low, allowing each individual feeding event to produce radio jets aligned with the axis of the obscuring torus, which itself is uncorrelated with the large–scale structure of the host galaxy. Our picture predicts that star formation should occur at radii comparable with those of the ring of young stars observed about the Galactic Centre. In an earlier paper (King & Pringle, 2006) we showed that small–scale feeding events allow supermassive black holes to reach large ($\gtrsim 10^9 M_\odot$) masses at high redshifts $\sim 6$. We conclude that small–scale chaotic feeding offers a promising explanation of the growth of most supermassive black holes, and thus for the activity of galactic nuclei.

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