Forced accretion in stochastically fed AGN and quasars

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ABSTRACT
Steady state accretion discs larger than \( \sim 0.01 - 0.1 \) pc are known to be gravitationally unstable for the accretion rates needed to explain super-massive black hole (SMBH) activity. We propose that SMBH are fed by a succession of mass deposition events with randomly directed angular momenta. Because of incomplete angular momentum cancellation a warped accretion disc forms in the inner few parsec. The orientation of the disc performs a random walk. Deposition of new material promotes SMBH accretion at rates much faster than viscous. Observational implications of this picture include: (i) lighter accretion discs that can fuel AGN and quasars and yet avoid star formation at \( R > \sim 0.1 \) pc; (ii) star formation inside the disc is not a function of mass accretion rate only. It can take place at high or low accretion rates, e.g., when too few clouds arrive in the inner region. An example of this might be the central parsec of our Galaxy. (iii) The discs can form Compton-thick obscuring structures of \( \sim \) parsec size as required in AGN unification models; (iv) faster black hole growth resulting from misalignment of the disc and the black hole spin in the early Universe; (v) Isotropic deposition of SMBH energy and momentum feedback in the galaxy bulge. This may help explain the high efficiency with which it seems to be operating in the Universe. (vi) No correlation between SMBH activity and the presence of kiloparsec scale bars or gaseous discs in galactic bulges; (vii) Bodily collisions between gaseous components of merging galaxies facilitate production of gas streams feeding the centre of the combined galaxy. Mergers should thus be catalysts of SMBH growth. (viii) Conversely, galaxies experiencing fewer mergers are more likely to form massive nuclear star clusters than feed their SMBHs.

Key words: Galaxy: centre – accretion: accretion discs – galaxies: active

1 INTRODUCTION
A well known difficulty in fuelling active galactic nuclei (AGN) is that the typical angular momentum of gas in the galactic bulge is very large compared with that of the last stable orbit around a black hole (e.g., Krolik, 1999; Combes, 2001; Jogee, 2004). Assuming that the bulge is the reservoir ultimately supplying mass to the nucleus, the result is presumably a disc with the size of a fraction of the bulge radius, i.e., a fraction of a kiloparsec. The material at the inner edge of the disc would then have to give up its angular momentum rapidly enough to be able to lower itself in the SMBH potential well. This can perhaps be done through the action of stellar and gaseous bars and other gravitational torques (e.g., Shlosman et al., 1990).

However, there is no clear observational evidence for a link between AGN activity and the presence of “grand design” gas discs or stellar bars (Combes, 2003).

A further theoretical impasse for large scale gaseous discs is that even if material does reach the inner parsec scales, theory predicts that these discs are too cold and too massive, and thus should be unstable to gravitational fragmentation and star formation (e.g., Paczyński, 1977; Kolykhalov & Sunyaev, 1980; Shlosman & Begelman, 1989; Collin.

For SMBH feeding, star formation is a disease that threatens the very existence of accretion discs outside the “self-gravity radius”, \( R > \sim 0.1 \) pc (Goodman, 2003). If gaseous discs are turned into stellar discs, SMBHs cannot grow by gas accretion.

Faced with these and other theoretical difficulties, Goodman (2003) and King & Pringle (2007) suggested that AGN may be fed by a direct deposition of low angular material into the region \( R < R_{\text{sg}} \). The main difficulty for this suggestion is that the specific angular momentum of the orbit at \( R = R_{\text{sg}} \) is only \( l \sim 100 \) pc km/s, much smaller than the more typical \( l \sim 10^4 - 10^5 \) pc km/s at \( R = 10^2 - 10^3 \) pc.

On the other hand, the SMBH mass, though large, is only a tiny fraction (\( \sim 0.001 \)) of the stellar mass of the bulge

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Häring & Rix, 2004, and must be an even smaller fraction of the original gaseous mass from which the bulge is made. It thus seems not impossible that cloud-cloud collisions, supernova shocks, and galaxy mergers channel such a small fraction of bulge gas on nearly radial orbits ending up inside \( R < R_{\text{sg}} \). Unfortunately, a quantitative treatment of these processes would be very model-dependent and hardly constraining.

In this paper we note that gas feeding the SMBH does not actually need to have such a small angular momentum after all. We propose that SMBHs can be fed by clouds with angular momentum an order of magnitude higher, i.e., only when the disc would already have collapsed gravitationally. Feedback due to radiation and outflows from massive stars may appear much faster, perhaps as quickly as required by equation \( 2 \). However it is not obvious that the feedback will be spread uniformly enough in the disc. For a disk of scale height \( H \), radiation and outflows from a massive star would affect a surface area of size \( \sim \pi H^2 \) only. Thus, to heat up the whole disc, \( \sim (R/H)^2 \) massive stars are required. If we assume that one massive star forms from \( \sim 500 M_\odot \) of gaseous material for a Salpeter (1955) IMF, this would require disc mass of \( M_{\text{disc}} \sim 5 \times 10^3 M_\odot h_{-2}^{-3/2} \), where \( h_{-2} = 100H/R \). The corresponding star formation rate would be \( M_{\text{disc}}/t_{\text{dyn}} \sim 5 \times 10^3 M_\odot \text{year}^{-1} h_{-2}^{-3/2} M_\odot^1/2 R_{\text{pc}}^{-3/2} \). This seems to be too high for the central region of only a few parsecs.

In addition, analytical estimates (Navakshin & Cuadra, 2005) and numerical simulations (Navakshin et al., 2007) show that the stellar component of star forming discs decouples vertically from the gaseous disc when the total stellar mass becomes comparable to the gas mass. Since gas cools radiatively and stellar motions do not, stellar discs become more vertically extended, as in the Galactic disc in Solar neighbourhood. Feedback in massive star-dominated discs in AGN would thus occur mainly outside the gaseous disc, diminishing the efficiency of feedback deposition further.

Summarising, there does not appear to be a completely convincing way to avoid the self-gravity catastrophe for parsec-scale massive AGN discs. The fundamental problem is that these discs are very inefficient as far as angular momentum transfer is concerned. They need to be massive enough to provide a high enough rate of SMBH feeding, yet they cannot be hot enough to escape fragmentation. The simplest conclusion one can draw from this is that while such discs are probably very important for transferring huge amounts of gas into the inner parts of galaxies, they probably fail to fuel SMBHs.

## 2 CAN GRAND DESIGN ACCRETION FEED SMBH?

**Goodman (2003)** presented the most complete and up-to-date consideration of gravitational stability of different accretion disc models. The standard accretion flow model is gravitationally unstable beyond the self-gravity radius \( R_{\text{sg}} \), which is a function of the accretion rate in the disc, \( M \). A rough power-law fit to this dependence from Figure 1 in **Goodman (2003)** is

\[
R_{\text{sg}} \approx 0.01 \text{ pc } M^{-2/7},
\]

where \( M \) is in units of \( M_\odot \text{ year}^{-1} \). For astrophysically interesting accretion rates, then, \( R_{\text{sg}} \sim 0.01 - 0.1 \text{ pc} \). **Goodman (2003)** also found that none of the more sophisticated models avoids becoming self-gravitating at parsec-scale distances from the SMBH, unless an unspecified and very large energy source is applied to the disc to keep it hot enough. The required energy at 10 pc, for example, was at least that expected if all of the disc material was reprocessed by massive stars. **Goodman (2003)** also pointed out that even if a source for this energy was found, the disc may still be thermally unstable as the cooling times were much shorter than the local dynamical time. Furthermore, **Sirk & Goodman (2003)** demonstrated that such a high energy liberation rate near an AGN is actually in conflict with the observed spectra of typical AGN.

**Thompson et al. (2005)** proposed a starburst disc model which appears to overcome the difficulties noted by **Goodman (2003)**. These authors suggested parameterising the radial inflow velocity at a fraction of the disc sound speed, arguing that external torques or spiral density waves may deliver the required angular momentum transfer. This makes these discs lighter at a given accretion rate. Additionally, Thompson et al.’s star formation rate in the disc is limited by the action of energy and momentum feedback from massive stars and supernovae, allowing some fuel to trickle down all the way to the nucleus.

Without numerical analysis it is difficult to say whether this model will work for parsec-scale AGN discs. One problem is that of time scales. Gravitational collapse of the disc is expected to take place on the dynamical time scale,

\[
t_{\text{dyn}} = \frac{R^{1/2}}{G^{1/2} M_{\text{bh}}^{1/2}} \sim 10^3 R_{\text{pc}}^3 M_{\text{S}}^{-1/2} \text{ years}.
\]

**Thompson et al. (2005)** show that the disc cooling time is much shorter than the dynamical time in their model. On the other hand, the lifetime of massive stars is at least a few million years. Therefore, the supernovae contribution to the feedback might be activated too slowly in this model, i.e., only when the disc would already have collapsed gravitationally.

## 3 STOCHASTIC SMBH FEEDING

### 3.1 Large scale region

Figure 1 illustrates the schematics of the model we would like to explore here. We assume that during the epoch of bulge and SMBH growth, the gaseous medium feeding both of these can be crudely divided into two components (left panel of figure 1). The first is the dominant part of the gas with non-negligible angular momentum. This component forms a large scale gaseous disc that mainly forms stars...
Figure 1. Schematic representation of stochastic cloud AGN feeding. **Left:** large scale (100pc to 1 kpc) distribution of gas. Most of the gas has a significant angular momentum and is in a circularised large scale disc that contributes little to AGN feeding. The quasi-spherical halo of gas clouds produces clouds on small angular momentum orbits. **Right:** Zoom-in view of the central region (the inner parsecs). Clouds collide in the hatched “collision sphere”, and form a warped disc whose orientation changes stochastically. Lines of view clear of the clouds and warped disc yield type 1 AGN classification whereas lines of sight intersecting the disc or clouds present AGN as a type 2 source. Note that this division into Type 1 and 2 is caused by the inner stochastically oriented disc and is unrelated to the large-scale structure of the galaxy.

Figure 2. Illustration of the accretion disc structure in Figure 1. The outer disc extends from $R_{\text{in}} \sim 0.01$ pc to $R_{\text{out}}$. Accretion is driven by cancellation of angular momentum in collisions between the disc and infalling clouds. The inner viscous disc joins the outer one at $R = R_{\text{in}}$. A short viscous time keeps the inner disc flat and aligned with the inner fringes of the outer disc, but not necessarily aligned with the black hole spin. The outer disc is warped and can be highly disturbed, presenting a large solid angle for AGN illumination.

3.2 Collision sphere and disc formation

The right panel of Figure 1 zooms in on the inner parsecs of the model. Let $R_{\text{coll}}$ be the radius of the sphere centered on the SMBH that is “optically thick” to a typical gas cloud. Clouds collide, convert their bulk kinetic energy into heat which is radiated away rapidly, and become bound to the SMBH inside this region. The lower limit on $R_{\text{coll}}$ is given by the geometrical size of the infalling clouds themselves, as the different sides of the cloud then collide with each other. Observed interstellar clouds form structures on a range of scales, but scales of few parsec are most common (Elmegreen & Falgarone, 1996). We thus expect that $R_{\text{coll}} > 1$ pc.

The angular momentum of the clouds at $R_{\text{coll}}$ is at most the local circular orbital value, $l_{\text{coll}} = \Omega R_{\text{coll}}$. As clouds collide, they circularize and settle into a disc. The outer radius of the disc, $R_{\text{out}}$, is smaller than $R_{\text{coll}}$, and is controlled by the degree to which angular momentum is cancelled in these collisions.

To estimate it, define $\dot{N}$ as the average rate of number of clouds entering the collision sphere $R = R_{\text{coll}}$. The angular form of compact cloud. We reason further that there will be continuous production of clouds on nearly radial trajectories through cloud-cloud collisions, their gravitational scattering off each other or off star clusters, supernova driven shock waves, etc. We now consider the structure of the inner accretion flow assuming that these nearly radial clouds provide the dominant mechanism of SMBH feeding.
The AGN disc we consider has a very unusual feeding mode as the angular momentum of the material supplied to the disc fluctuates with arrival of new clouds. Unlike binary Roche lobe overflow systems, the geometry is 3D, with new material arriving not necessarily at the outer edge. In particular, parts of clouds with particularly low angular momentum might strike the disc further in than \( R_{\text{in}} \). In a clear difference from the standard accretion flow, no angular momentum transport is needed in such randomly fed discs to promote accretion. Cancellation of the randomly directed angular momentum of the new material and that of the disc sets up a radial inflow. We call this “forced accretion” as it is mediated by external deposition of material.

Let us estimate the steady-state mass of such a disc. The specific angular momentum of a disc containing \( N \) equal mass clouds that arrived with a random direction of the angular momentum will be \( \tilde{J}_{\text{disc}} \sim \tilde{J}_{\text{cloud}}/N^{1/2} \), again by random walk arguments. If this angular momentum is less than \( J_{\text{cloud}} \), the disc will move in (this in very simple picture) to \( R < R_{\text{in}} \). Thus, \( N = (\tilde{J}_{\text{cloud}}/J_{\text{cloud}})^2 \) random cloud deposition events are needed to lower the gas to \( R < R_{\text{in}} \) region. Accordingly, the “stochastic average” mass of the disc will be

\[
M_{\text{disc}} = M_1 N \sim N \left( \frac{\tilde{J}_{\text{cloud}}}{J_{\text{cloud}}} \right)^2 = \frac{M_1 R_{\text{cloud}}}{R_{\text{in}}},
\]

where \( M_1 \) is the mass of a cloud. For example, if \( M_1 = 100 M_{\odot} \) and \( R_{\text{cloud}}/R_{\text{in}} = 300 \), then \( M_{\text{disc}} \) is \( \sim 3 \times 10^4 M_{\odot} \). The accretion time scale is given by the expression

\[
t_{\text{acc}} = \frac{N}{R_{\text{in}}} \frac{R_{\text{in}}}{R_{\text{cloud}}} M_1 \frac{1}{N}.
\]

In a quasi steady state, the surface density profile, \( \Sigma(R) \), is a strongly peaked function for these discs. We have, const=\( \dot{M} \sim \Sigma(R)\pi R^2 t_{\text{acc}}^{-1} \). As \( t_{\text{acc}} \) is independent of radius, we obtain \( \Sigma(R) \propto R^{-2} \). This is a much steeper dependence than that for discs in which surface density is regulated by angular momentum transfer, since viscous time typically is a strongly increasing function of radius. For example, for a standard gas-dominated accretion disc, \( \Sigma \propto R^{-3/4} \) (Shakura & Sunyaev, 1973).

Consider gravitational stability of such discs. In our model the heating per unit surface area is \( Q^{+} = \Sigma \Omega^2 R^2 t_{\text{acc}}^{-1} \). The radiation flux emerging from the disc is \( \alpha T^4 (\tau + 1/\tau)^{-1} \), where \( T \) is disc midplane temperature and \( \tau \) is the optical depth of the disc. Since \( \tau > 1/\tau \), we can estimate the disc temperature to be

\[
T > \left[ \frac{\Sigma \Omega^2 R^2}{\alpha t_{\text{acc}}} \right]^{1/4}.
\]

Further, if we take into account gas pressure only, we obtain the minimum scale height of the disc as \( H = c_s \Omega^{-1} = (kT/\mu)^{1/2} \Omega^{-1} \). Requiring \( \Sigma_{\text{disc}} \approx \Sigma R^2 \gtrsim M_{\text{th}}(H/R) \), we arrive at the minimum disc mass required for gravitational instability in our model:

\[
M_{\text{th}} \geq \frac{k^4 R}{G^3 \mu^4 M_{\text{th}}^2 \sigma t_{\text{acc}}} \approx 0.002 \frac{R_{\odot} M_{\odot}^{2/5} t_5}{M_{\odot}^{2/5} t_5^{1/7}},
\]

where \( M_{\odot} = M_{\text{th}}/10^8 M_{\odot}, t_5 = t_{\text{acc}}/10^5 \) years. In the latter we set \( \mu = m_{p} \). Equation 4 allows us to estimate the minimum accretion rate at which these discs would become self-gravitating:

\[
M_{\delta} = \frac{M_{\text{th}}}{t_{\text{acc}}} \geq \frac{2 M_{\odot}}{\text{year}} \frac{R_{\odot} M_{\odot}^{2/5} t_5^{1/7}}{M_{\odot}^{2/5} t_5^{1/7}}.
\]

Note that the dependence on the radius is quite weak here. Apparently, such externally fed accretion flows are able to deliver accretion rates of the order of the Eddington accretion rate of the SMBH if the time scale on which the angular momentum of the incoming gas fluctuates is shorter than \( t_{\text{acc}} \geq t_{\text{stoch}} \sim 10^5 \) years.

This time scale can be much shorter than the disc viscous time, \( t_{\text{visc}} \sim \alpha^{-1} (R/H)^2 \Omega^{-1} \) at parsec distances from the SMBH (Shakura & Sunyaev, 1973).

We can estimate the maximum outer radius of the externally forced discs. Requiring that the time scale for a significant angular momentum change \( t_{\text{acc}} \geq t_{\text{visc}} \) to be larger than the local dynamical time given by equation 2 we see that the disc cannot be larger than about 10 pc. Another way to put this result is to say that any disc larger than this will necessarily be star forming.

3.4 Inner viscous disc

At small radii, the viscous time is shorter than \( t_{\text{acc}} \). Within that region, the inflow is viscous rather than externally driven. The inner radius of the forced discs can thus be estimated as

\[
R_{\text{in}} \approx 0.01 \text{ pc} \alpha_{2/3} h_{2}^{4/3} t_{5}^{2/3} M_{\odot}^{1/3},
\]

where \( h_{2} = 100 H/R \) is the aspect ratio of the inner disc. This is an estimate only, as hydrogen ionisation instability might in principle be important for this region (e.g., Siemiginowska & Elvis, 1997) and modulate the accretion rate onto the SMBH.

Lodato & Pringle (2007) show that, in a diffusive regime, warp propagation occurs on a time scale shorter than the viscous time by a factor \( \alpha_{2}/\alpha_{1} \), where \( \alpha_{2} \) is the “warp diffusion viscosity coefficient”. They find that \( \alpha_{2} \) has a maximum value of a few which is attained for strongly warped accretion discs. Hence, in the context of our model, the inner region of radial size

\[
R_{\text{inv}} \approx 0.1 \text{ pc} \left( \frac{\alpha_{2}}{3} \right)^{2/3} h_{2}^{4/3} t_{5}^{2/3} M_{\odot}^{1/3},
\]

\[2 \text{ a finite disc opacity and the radiation contribution to the disc pressure, both neglected above, will make this only limit higher}\]
is able to flatten out due to local viscous forces. The inner flow then consists of the innermost zone \((R < R_{\text{in}})\) where the flow is flat and viscosity mediates the inflow, and the outer zone \((R_{\text{in}} < R < R_{\text{flat}})\), where the disc is also flat but the inflow is driven by the same mechanism as in the larger forced disc. The orientation of the inner disc \(R < R_{\text{flat}}\) coincides with the that of the innermost part of the larger forced disc.

Note that \(R_{\text{flat}}\) sets a velocity scale — the Kepler velocity at that radius \(v \approx \text{few} \times 10^2 \text{ km s}^{-1}\). Since the inner disc is flat, it presents a very small solid angle to the AGN illumination. On the other hand, the outer disc might be much better exposed to the AGN. It is then possible that the transition between the inner flat and the outer warped disc will be a site for broad AGN optical and UV lines. We would then predict, in the context of our model, that the broad line features should have velocity widths of order of a few thousand \(\text{km s}^{-1}\).

4 IMPLICATIONS

Avoiding the self-gravity catastrophe. The picture of accretion proposed above suggests that stochastically fed AGN accretion discs can extend beyond the self-gravity radius \(R_{\text{sh}}\). These discs are not subject to the self-gravity catastrophe as long as the gas feeding these has a random sense of angular momentum fluctuating on time scales \(t \leq t_{\text{iso}}\). This then ensures that super-massive black holes can grow via gas accretion, as required by the observations (Yu & Tremaine, 2002).

Note that our model is related to the proposals made by Goodman (2003) and especially King & Pringle (2007) that material feeding AGN comes in shots directly impacting the AGN. These discs are not subject to the self-gravity catastrophe as long as the gas feeding these has a random sense of angular momentum fluctuating on time scales \(t \leq t_{\text{iso}}\). This then ensures that super-massive black holes can grow via gas accretion, as required by the observations (Yu & Tremaine, 2002).

Nuclear star formation. In our model, star formation in the direct vicinity of a SMBH is a function of not only the gaseous mass deposited there but also the manner in which that mass arrived there. In particular, contrary to steady-state viscous accretion flows, it is feasible to have mainly accretion at a high mass deposition rate, but mainly star formation at lower rates. An example of the latter situation could be the central parsec of our Galaxy, where two young stellar rings have apparently formed in situ about \(\approx 6\) Million years ago (Levin & Beloborodov, 2003; Genzel et al., 2003). A reasonable explanation of this is an inflow of two clouds with mass of a few thousand to \(\sim 10^3 \text{M}_\odot\) (Nayakshin & Cuadra, 2005; Paumard et al., 2006). Coeval infall of several more clouds of this type from random directions could have led to more angular momentum cancellation and mainly accretion of gas on Sgr A* instead of star formation.

There is no one-to-one relation between AGN activity and nuclear starbursts in this picture, as it is possible in principle to have either one separately. On the other hand, AGN feeding in our model depends on availability of gas clouds on low angular momentum orbits. Star formation feedback (outflows and supernovae) may be encouraging such orbits via adding large random velocity kicks to gas clouds in vicinity. Thus, statistically it is more likely that starbursts and AGN would be linked to one another.

Masing and/or star forming rings in nearby AGN. If SMBHs are fed by grand design discs, the surface density distribution is normally a continuous well behaved function, such as a power-law. In contrast to that, if accretion is stochastic, then the disc surface density distribution does not have to be a smooth function, particularly at lower cloud deposition rates. In particular, rings with radial extent \(\Delta R \sim R\) might result. Observationally this might be relevant to masing discs in nearby AGN, where the radial extent of the emitting region is usually narrow. If rings are massive enough, stellar discs with well defined inner and outer edges may form in this way.

Random SMBH jet orientation, faster early SMBH growth. As pointed out by King & Pringle (2007), the spin of a black hole fed by deposition of clouds with randomly directed angular momentum will be frequently misaligned with that of the inner accretion disc. This leads to a smaller radiative efficiency and a faster black hole growth, helping to explain the heavy-weight champion SMBHs observed already at high redshifts (tbd). Furthermore, Schmitt et al. (2002) pointed out that jets in radio galaxies seem to be oriented (almost) randomly with respect to dust discs of these galaxies. This would be natural in our model.

The \(M_{\text{bh}}-M_{\text{bulge}}\) correlation. Models explaining the correlation between the observed SMBH masses and the bulge masses hosting them as arising due to SMBH accretion feedback seem to be promising (King, 2003). These models postulate that gas located throughout the bulge can be overheated or swept away by the SMBH feedback. If SMBH were fed from a large scale massive gaseous disc with a small \(H/R\) ratio, it would be very hard to affect that gas reservoir.

The difficulty in expelling a flat disc is two fold: (i) Firstly, the column depth of the gaseous disc with mass \(M_d\) through the midplane of the disc is \(\sim M_d/(R H)\). This is \(R/H\) times higher than the column depth of spherically distributed material with same mass, \(\sim M/R^2\). Hence it is harder to affect the disc with feedback of any type. (ii) Secondly, the SMBH feedback may well be collimated and oriented perpendicular to the inner accretion disc. If the inner disc is oriented same way as the much larger disc in the bulge, then the feedback may miss the disc altogether.

A numerical illustration of these principles is provided by the recent calculation of the radiation field during build up of a high mass protostar by Krumholz et al. (2003). These simulations show that if outflow is collimated, then the radiation field is also collimated and therefore affects the infalling material significantly less than previously thought.

Thus, there does not seems to be a way to expel either the disc from the bulge or shut off SMBH feeding if this originates in a massive flat disc. On the other hand, if material feeding the SMBH is distributed quasi-isotropically throughout the bulge, and if the direction of the SMBH spin (and feedback) randomly fluctuates, then the arguments made by...
Absence of a correlation between AGN activity and presence of bars. If SMBH is not fed by the large scale grand design gaseous features such as spirals or bars, then the latter have no bearing on AGN activity, as observed.

Importance of mergers in AGN feeding. Here we have argued that SMBH fuelling is driven by infall of gas on nearly radial trajectories. For the gas at $R \sim R_{\text{bulge}}$ to assume such an orbit, the angular momentum of (only some!) clouds needs to cancel out almost completely by cloud-cloud collisions, for example. A way of putting much more gas on such orbits would be to have a major merger, in which the gaseous discs of the galaxies collide bodily. Such collisions probably generate SMBH feeding rates well in excess of the Eddington rate since the gaseous discs can be orders of magnitude more massive than the SMBHs.

Nuclear star clusters and SMBH in dwarf galaxies. Galaxies going through fewer mergers channel less gas on nearly radial orbits. Central black holes in these galaxies are thus relatively more “fuel starved” than their cousins in galaxies experiencing more mergers. SMBHs in such “no mergers” galaxies could then be underweight compared to their expected $M_{\text{bh}}-M_{\text{bulge}}$ or $M_{\text{bh}}-\sigma$ mass. If smaller galaxies go through fewer mergers, as current cosmological simulations imply, then it is these galaxies, i.e., dwarf spheroidals, that are most strongly affected by this argument. The fuel stalled in the central region of the galaxy because of insufficient angular momentum cancellation can be used up in nuclear star formation. These ideas might be relevant to the recently claimed dichotomy of nuclear star clusters and SMBHs in observations (e.g., Wehner & Harris, 2006), with the former objects present mainly in low mass galaxies, and with dwarf spheroidals possibly lacking SMBHs.

The final parsec problem for SMBH mergers. It is found that central black holes in a major merger always find their way into the central part of the resulting galaxy by dynamical friction (e.g., Begelman et al., 1980). These black holes then form a binary. The SMBH binary continues to shrink by expelling stars. However, when the binary separation approaches a few parsec, interactions with the stellar background become too inefficient. If gas continues to pile up in the inner few parsecs of the galaxy through stochastic cloud deposition, the SMBH pair can do work on this supposedly unlimited gas supply instead of stars, and continue to shrink until gravitational radiation takes over (for related ideas see Escala et al., 2003).

Unification and obscuration schemes of AGN. Warped accretion discs have been claimed to be important in the obscuration of the inner regions of type II AGNs (Nayakshin, 2003). Stochastically fed accretion discs are generically strongly warped because different mass “shots” will likely have not only random angular momentum orientation and also different circularisation radii. Further, it can be shown that time scales for flattening the warps can be much longer than $t_{\text{sto}}$ (except for the inner disc, see §3.3). We have shown that our disc model is gravitationally stable for disc masses less than $M_{\text{disc}} \sim 0.002 M_{\text{bh}}$ (see equation (7)). The column depth of a such a disc is then

$$\Sigma \sim \frac{M_{\text{disc}}}{\pi R^2} \sim 20 \frac{M_{\text{bh}}}{R_{\text{pc}}} R_{\text{pc}}^{13/7} t_5^{-1/7},$$

Thus, if these discs are strongly warped, they could form Compton-thick absorbers with size of at most a few parsec. This agrees with estimates for the obscuring medium inferred in AGN.

Absence of type II LLAGN. In our picture, Low Luminosity AGN would deposit mass at a low rate or always with the same angular momentum. In either case this would imply a disc passively circling the SMBH at the circularisation radius or perhaps forming stars if the disc becomes too massive. In the first case, the disc may well have enough time to flatten out by viscous or gravitational torques, whereas in the other the disc might be consumed by star formation too rapidly to provide a large enough obscuring column depth, therefore, in general we predict that LLAGN must be much less obscured than brighter AGN such as Seyfert Galaxies.

5 DISCUSSION AND CONCLUSIONS

In this paper we have considered SMBH feeding in galaxies. We suggest that due the extremely long time scales for angular momentum transfer and the loss of gas to star formation mean that large scale gas discs do not contribute directly to SMBH growth. Instead, we argue that SMBHs are fuelled by low angular momentum gas. Our model is closely related to suggestions made by Goodman (2003) and King & Pringle (2007), as the core idea is that the angular momentum of the incoming gas is small in a time-averaged sense. However, our model has additional observational implications. For example, warped “externally forced” accretion discs can extend to scales of up to 10 pc (see the end of §3.3), which is much larger than the self-gravity radius $R_{\text{eq}} \sim 0.01–0.1$ pc.

One question that we do not address here is whether real galaxies feed enough gas on nearly radial trajectories to support the growth of their SMBHs. This requires numerical simulations of a significant dynamic range and physical complexity.

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