

# Competitive feedback in galaxy formation

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## ABSTRACT

It is now well established that many galaxies have nuclear star clusters (NCs) whose total masses correlate with the velocity dispersion  $\sigma$  of the galaxy spheroid in a very similar way to the well-known supermassive black hole (SMBH)  $M$ – $\sigma$  relation. Previous theoretical work suggested that both correlations can be explained by a momentum feedback argument. Observations further show that most known NCs have masses  $\lesssim 10^8 M_\odot$ , while SMBHs frequently have measured masses  $\gtrsim 10^8 M_\odot$ , which remained unexplained in earlier treatments. We suggest here that this changeover reflects a competition between the SMBH and nuclear clusters in the feedback they produce. When one of the massive objects reaches its limiting  $M$ – $\sigma$  value, it drives the gas away and hence cuts off its own mass and also the mass of the ‘competitor’. The latter is then underweight with respect to the expected  $M$ – $\sigma$  mass.

More specifically, we find that the bulge dynamical time-scale is a steeply rising function of velocity dispersion, and that the NC–SMBH changeover occurs where the dynamical time is about equal to the Salpeter time. We propose that SMBHs, growing on the Salpeter time-scale, are unable to reach their  $M$ – $\sigma$  mass quickly enough in small bulges. The central regions of these bulges are swamped with gas which fragments into stars, creating the nuclear clusters. The latter then limit their own growth by the feedback they produce, settling on their (offset)  $M$ – $\sigma$  relation. The SMBH in such bulges should be underweight as their growth is curtailed before they reach the  $M$ – $\sigma$  mass. In large bulges, on the other hand, the SMBH catches up quickly enough to settle on its  $M$ – $\sigma$  relation. Nuclear star clusters may also exist in such bulges but they should be underweight with respect to their  $M$ – $\sigma$  sequence.

**Key words:** accretion, accretion discs – galaxies: active – galaxies: formation.

## 1 INTRODUCTION

It is well known that the masses of the supermassive black holes (SMBHs) in the nuclei of early-type galaxies and bulges correlate with the velocity dispersions of the stellar spheroids (e.g. Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002). A simple explanation invokes momentum feedback (King 2003, 2005). In this picture, the SMBH luminosity is limited by the Eddington value, and the momentum outflow rate produced by radiation pressure is of the order of

$$\dot{M}_{\text{SMBH}} \approx \frac{L_{\text{Edd}}}{c} = \frac{4\pi G M_{\text{BH}}}{\kappa}, \quad (1)$$

where  $\kappa$  is the opacity, assumed to be dominated by the electron scattering, and  $M_{\text{BH}}$  is the SMBH mass. This momentum flux produces an outward force on the gas in the bulge, whose weight is  $W(R) = GM(R)[M_{\text{total}}(R)]/R^2$ , where  $M(R)$  is the enclosed gas mass at radius  $R$ , and  $M_{\text{total}}(R)$  is the total enclosed mass including

dark matter. For an isothermal potential,  $M(R)$  and  $M_{\text{total}}(R)$  are proportional to  $R$ , so the result is

$$W = \frac{4f_g\sigma^4}{G}, \quad (2)$$

where  $f_g$  is the baryonic fraction and  $\sigma^2 = GM/2R$  is the velocity dispersion in the bulge. To order of magnitude, the relation (2) holds for any potential if estimated at the virial radius.

Requiring that momentum output produced by the black hole should just balance the weight of the gas leads to the  $M_{\text{BH}}$ – $\sigma$  relation (King 2003, 2005):

$$M_{\text{BH}} = \frac{f_g\kappa}{\pi G^2}\sigma^4. \quad (3)$$

The model is attractive in its physical simplicity. Further, the result contains no free parameters, but is very close to the observed  $M_{\text{BH}}$ – $\sigma$  relation.

Another feature commonly found in the centres of galaxies is nuclear star clusters. They are found in late-type spirals (e.g. Böker et al. 2002), bulgeless spirals (Walcher et al. 2005), edge-on spirals (Seth et al. 2006) and dwarf elliptical galaxies (Côté et al. 2006). The cluster masses range from  $10^6$  to  $10^8 M_\odot$  (although even more

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massive clusters have been found recently by Kormendy et al. 2009), whereas their sizes are only a few to a few tens of parsecs. Intriguingly, for dwarf ellipticals the masses of NCs correlate with the host properties. Namely, Ferrarese et al. (2006) found that the NC mass is related to the bulge velocity dispersion in exactly the same way as the SMBH–velocity dispersion relation, but with normalization offset by about an order of magnitude. The cluster masses are also almost linearly proportional to the total bulge mass (Ferrarese et al. 2006; Wehner & Harris 2006).

McLaughlin, King & Nayakshin (2006) proposed that the observed  $M_{\text{NC}}-\sigma$  relation for dwarf elliptical galaxies follows naturally from an extension of the above argument (King 2003, 2005) to the outflows from young star clusters containing massive stars. These individual stars are also Eddington limited, and produce outflows with momentum outflow rate  $\sim L_{\text{Edd}}/c$  where  $L_{\text{Edd}}$  is calculated from the star’s mass. Young star clusters with normal initial mass functions (IMFs) produce momentum outflow rate:

$$\dot{P}_{\text{NC}} \approx \lambda \frac{L_{\text{Edd}}}{c}, \quad (4)$$

where  $\lambda \approx 0.05$  and  $L_{\text{Edd}}$  is now formally the Eddington value corresponding to the total cluster mass. To produce the same amount of momentum feedback, a young star cluster must therefore be  $1/\lambda$  times more massive than an SMBH radiating at the Eddington limit, and hence

$$M_{\text{NC}} = \frac{f_g \kappa}{\lambda \pi G^2} \sigma^4. \quad (5)$$

Strikingly,  $1/\lambda$  is quite close to the offset in mass between the  $M_{\text{BH}}-\sigma$  and  $M_{\text{NC}}-\sigma$  relations. Furthermore, while equation (1) is very plausible (see King & Pounds 2003), the momentum outflow rates from stars are known in detail observationally. The largest uncertainty in equation (4) is therefore the stellar IMF, which is observationally fairly constant (e.g. Kroupa 2002). The McLaughlin et al. (2006) explanation of  $M_{\text{NC}}-\sigma$  relation thus appears similarly robust to the King (2003, 2005) model for SMBH feedback.

However, McLaughlin et al. (2006) did not offer an explanation of why bulges with smaller  $\sigma$  contain nuclear clusters, while more massive galaxies contain SMBHs and not NCs. Here, we propose an explanation, noting that time-scales are important in this problem as well as energetics.

Our simple theory for the observed bimodality of NC and SMBHs is based on the premise that the dominant object must be able to grow quickly and yet stay active for long enough to provide the needed feedback. As we show below, in small bulges this argument favours nuclear star clusters whereas in larger ones the situation is reversed. Below, we explain our idea, address observational constraints and conditions needed for it to work, and suggest possible astrophysical implications.

We note that nuclear star clusters could in principle form elsewhere in the galaxies and then migrate inwards due to dynamical friction with the background stars. However, Milosavljević (2004) argues against this possibility due to the short time-scales available for this process, and argues instead that these clusters may form *in situ*. We agree with this point, and further note that observations of young massive stars in the central parsec of the Milky Way offer direct support to the *in situ* formation model (Nayakshin & Cuadra 2005; Paumard et al. 2006; Nayakshin & Sunyaev 2005). The exact geometrical arrangement of the forming stars (a thick disc or a quasi-spherical cluster) is irrelevant on the scales of the parent galaxy.

## 2 TIME-SCALES

Black holes and nuclear clusters each evolve on characteristic time-scales. SMBH growth is limited by the Eddington accretion rate,  $\dot{M}_{\text{Edd}} = L_{\text{Edd}}/(\epsilon c^2)$ , where  $\epsilon \sim 0.1$  is the radiative efficiency of accretion. SMBH masses can grow no faster than  $\exp(t/t_{\text{Salp}})$ , where

$$t_{\text{Salp}} = \frac{M_{\text{BH}}}{\dot{M}_{\text{Edd}}} = \frac{\kappa \epsilon c}{4\pi G} = 4.5 \times 10^7 \epsilon_{0.1} \text{ yr} \quad (6)$$

is the Salpeter time, with  $\epsilon_{0.1} = \epsilon/0.1$ . Star formation can occur on the free-fall or dynamical time-scale  $t_{\text{dyn}}$  of the system, which is less than a million years for many observed young star clusters (e.g. Hillenbrand 1997).

Once a SMBH is created, its feedback can be activated at any time, provided that the accretion rate is high enough. By contrast, star cluster feedback has a ‘half life’ of around  $t_{\text{MS}} \lesssim 2 \times 10^7$  yr, since this is the main-sequence lifetime of the massive stars contributing most to the feedback (e.g. Leitherer et al. 1992). This time-scale is only a factor of 2 shorter than the Salpeter time. After this time ( $t = t_{\text{MS}}$ ), the ability of the nuclear clusters to expel gas from the galaxy is severely reduced. They would have to be rebuild their population of massive young stars to restart. It is not obvious that this is physically possible inside an existing dense stellar cluster.

Consider a bulge where the dynamical time (equation 7 below) is much shorter than the Salpeter time. In a gas-feeding event (e.g. a merger), the bulge regains dynamical equilibrium before any significant SMBH growth and feedback set in, and there is nothing to prevent gas from collecting in the bulge centre. The accumulated gas is then consumed by star formation in nuclear regions, forming nuclear clusters which quickly reach their  $M_{\text{NC}}-\sigma$  limiting mass. This cuts off growth of everything – the bulge, the NC and the SMBH as well. The SMBH in these bulges is thus bound to be underweight compared to the  $M_{\text{BH}}-\sigma$  relation.

In the opposite extreme, when the bulge dynamical time is longer than the Salpeter time, the SMBH can grow quickly enough to reach its limiting  $M_{\text{BH}}-\sigma$  mass. While nuclear star clusters might be created there as well, their feedback quickly (i.e. in about 20 million years) becomes negligible. The situation is thus the reverse of the last paragraph, and it is the nuclear star clusters that are underweight in these bulges.

Below, we estimate  $t_{\text{dyn}}$  as a function of bulge mass or velocity dispersion. We find that  $t_{\text{Salp}} \gtrsim t_{\text{dyn}}$  in smaller bulges ( $\sigma \lesssim 150 \text{ km s}^{-1}$ ) and  $t_{\text{Salp}} \lesssim t_{\text{dyn}}$  in larger ones.

## 3 DYNAMICAL TIME AND VELOCITY DISPERSION

A tacit but obvious assumption in the arguments of King (2003, 2005) and McLaughlin et al. (2006) is that the source of feedback can respond quickly to bulge growth and thus influence it. Depletion of gas in the bulge by star formation and the onset of stellar feedback probably occur within a few bulge dynamical time-scales:

$$t_{\text{dyn}} = \frac{R}{\sigma}, \quad (7)$$

where  $R$  and  $\sigma$  are the scalelength and velocity dispersion of the bulge. If the feedback source fails to reach its limiting mass, its feedback remains unimportant.

We now consider how the dynamical time  $t_{\text{dyn}}$  scales with the  $\sigma$  of the stellar component of a galaxy. It is well established that

stellar spheroids occupy a two-dimensional ‘Fundamental Plane’ in the space defined by the total luminosity, the scalelength and the velocity dispersion (Djorgovski & Davis 1987; Bernardi et al. 2003). The plane is tilted relative to its position expected from the virial theorem for a homologous population of galaxies in a dynamical equilibrium. Several explanations for the origin of the tilt have been discussed in the literature, including systematic variations in the mass-to-light ratio of the stellar populations or changes in the dark matter fraction (e.g. Dekel & Cox 2006). Recent studies have shown that the tilt is essentially independent of the wavelength of the observations, suggesting that stellar population variations are not the dominant contribution (Bernardi et al. 2003; La Barbera et al. 2008).

Projections of the Fundamental Plane lead to a number of simple scaling relations. Using Sloan Digital Sky Survey photometric and spectroscopic data for  $\sim 9000$  galaxies with measured velocity dispersions of  $100\text{--}400\text{ km s}^{-1}$ , Bernardi et al. (2003) derived the following relations between  $R$ ,  $\sigma$  and the total luminosity  $L$ :

$$R = 2.6 \left( \frac{L}{1.6 \times 10^{10} L_{\odot}} \right)^{0.704 \pm 0.025} \text{ kpc}, \quad (8)$$

$$\sigma = 150 \left( \frac{L}{1.6 \times 10^{10} L_{\odot}} \right)^{0.23 \pm 0.012} \text{ km s}^{-1}. \quad (9)$$

[The power-law indices are taken from Dekel & Cox (2006) who report updated values obtained by Bernardi (private communication) using revised SDSS photometry.] These relations lead to another one between the dynamical time and the total luminosity, given by

$$t_{\text{dyn}} = \frac{R}{\sigma} = 17 \left( \frac{L}{1.6 \times 10^{10} L_{\odot}} \right)^{0.474} \text{ Myr}. \quad (10)$$

Combining relations (9) and (10), we obtain the dynamical time as a function of velocity dispersion, namely

$$t_{\text{dyn}} = 17 \left( \frac{\sigma}{150 \text{ km s}^{-1}} \right)^{2.06} \text{ Myr}. \quad (11)$$

We have taken  $\sigma \sim 150 \text{ km s}^{-1}$  as our fiducial value as the observations show that no nuclear clusters have been observed in systems with  $\sigma \gtrsim 150 \text{ km s}^{-1}$ . The above relations show that this roughly coincides with the transition between systems with dynamical times longer than the Salpeter time (6). The details of the transition may depend on the merger history of the galaxy.

#### 4 DISCUSSION

We have seen that momentum feedback gives a simple physical explanation of why galaxy bulges are dominated by nuclear clusters for low velocity dispersions and by SMBHs for high dispersions. We have emphasized that given an injection of gas, e.g. from a merger, galaxies with dynamical times shorter than the Salpeter time cannot grow their central black holes sufficiently quickly to affect the gas infall. Gas accumulating in the central regions cannot cool and condense indefinitely, so nuclear star clusters form and produce feedback. The masses of these clusters saturate at the mass (5) when they expel the remaining gas. The hole thus remains close to its ‘seed’ mass, which is presumably less than the value (3).

Note that this line of argument does not imply that dwarf elliptical galaxies with low velocity dispersion do not contain massive black holes. We only suggest here that their growth is slow; it is not entirely forbidden. Therefore, these galaxies may still contain underweight SMBH, i.e. black holes with mass significantly less

than the corresponding  $M_{\text{BH}}\text{--}\sigma$  value. It seems difficult to avoid building up a massive black hole in the very centre of the cluster and galaxy potential well. Mergers of low mass holes may provide an interesting additional window for gravitational wave astronomy (Matsubayashi, Shinkai & Ebisuzaki 2004; Amaro-Seoane, Miller & Freitag 2009).

There is an important constraint for our model to be applicable. Star formation in the inner parts of galaxies with higher velocity dispersions is not ruled out by the considerations of this Letter. These galaxies could thus potentially build up nuclear clusters in their centres. If this happens faster than the Salpeter time then the masses of these clusters should saturate at the value (3). Presumably, if the SMBH continues to grow at the Eddington rate, it could then reach its limiting  $M_{\text{BH}}\text{--}\sigma$  mass. However, this picture would predict very massive nuclear star clusters (up to  $M_{\text{NC}} \sim 10^{10} M_{\odot}$  for  $\sigma \sim 300 \text{ km s}^{-1}$ ) which are not observed.

This suggests that SMBH growth by accretion should be the dominant process in the central parsecs of galaxies, and that star formation occurs only as an alternative when gas cannot be consumed by the hole quickly enough. The latter naturally occurs if (i) the material is first deposited into the disc on small scales where star formation does not occur due to the strong SMBH tidal effect (e.g. Kolykhalov & Sunyaev 1980; King & Pringle 2007) and (ii) the hole is fed at a super-Eddington rate. Then the hole accretes the gas at the Eddington rate, expelling the rest. A good fraction of the expelled gas would probably not travel very far from the centre of the galaxy. Gas is likely to be expelled with a range of velocities, some too low to escape to infinity. As its angular momentum is very low, the gas can fall back into the inner parsec(s). Such effects are actually observed in the simulations of accretion disc winds by Proga (2003). Deposited back into the accretion disc on parsec scales, the gas would then fuel star formation there (e.g. Goodman 2003).

Summarizing this, the applicability of our model demands that SMBH feeding be primary and star formation secondary in the inner few parsecs of active galactic nuclei. If this holds, nuclear star clusters grow only when SMBHs cannot.

Finally, our model explicitly assumes that the nuclear star clusters and bulges of dwarf ellipticals form in a quasi-spherical or at least a geometrically thick disc configuration of gas. If instead the gas is in a thin disc configuration before the onset of star formation, the feedback efficiency would be greatly reduced, and no significant bulge would be formed. Therefore, our model does not apply to bulgeless spiral galaxies. If the central  $\lesssim$  tens of parsecs of these galaxies are fed via gaseous discs (e.g. Milosavljević 2004) then the mass of the NCs need not saturate at the value given by equation (5).

The assumption that star formation proceeds on a single dynamical time-scale is a lower limit on the time actually required. In fact, it is more likely that star formation in the bulge takes several dynamical times to complete. Indeed, observationally we know that giant molecular clouds in the Milky Way must be contracting much more slowly than dynamical collapse (Zuckerman & Palmer 1974) to explain the low star formation efficiency in the Galaxy, presumably due to feedback by star formation inside the clouds (McKee 1989). We would therefore expect a transition regime around  $\sigma \sim 150 \text{ km s}^{-1}$  where galaxies may contain either nuclear clusters or black holes. This boundary region extends over a factor of  $\sim 2$  in  $\sigma$ . In this region, the competition between NCs and SMBH depends on the detail of gas deposition in the inner region of the galaxy and perhaps the merger history of the galaxy.

The picture we have presented is necessarily very simplified. One would like to include effects such as a realistic galaxy bulge

potential, density inhomogeneities and possible cooling effects. Further, the changeover between NC and SMBH-dominated bulges depends on the merger history of the galaxy. For all these reasons, a numerical treatment of this picture is desirable. The fact that our own Galaxy appears to lie in the regime where the merger history may play an important role should make such studies rewarding.

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