Feedback from Nuclear Star Clusters (NCs) and SMBHs

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Abstract. The observed super-massive black hole (SMBH) mass – galaxy velocity dispersion \( (M_{\text{cmo}} - \sigma) \) correlation, and the similar correlation for nuclear star clusters, may be established when winds/outflows from the CMO (“central massive object”) drive gas out of the potential wells of classical bulges. Timescales of growth for these objects may explain why smaller bulges appear to host preferentially NCs while larger ones contain only SMBHs.

Despite much recent progress, feedback processes in bulge/galaxy formation are far from being understood. Our numerical simulations show that understanding how the CMO feeds is as important a piece of the puzzle as understanding how its feedback affects its host galaxy.

1. Analytical arguments for \( M_{\text{cmo}} - \sigma \) relations

It is believed that the centres of most galaxies contain SMBHs whose mass \( M_{\text{bh}} \) correlates with the velocity dispersion \( \sigma \) of the host galaxy [Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002]. Similarly, there is a correlation between \( M_{\text{bh}} \) and the mass of the bulge, \( M_{\text{bulge}} \), for large SMBH masses (Magorrian et al. 1998; Haring & Rix 2004; Gültekin et al. 2009). Observations also suggest that the masses of NCs \( (10^5 M_\odot < M_{\text{NC}} < 10^8 M_\odot) \) correlate with the properties of their host dwarf ellipticals [Ferrarese et al. 2006; Wehner & Harris 2006] in a manner that is analogous to the one between SMBHs and their host ellipticals.

These relations can be explained in a similar way if the growth of host galaxies and their central SMBHs or NSCs are linked by momentum feedback. In the model of King (2003, 2005), the SMBH luminosity is assumed to be limited by the Eddington value. Radiation pressure drives a wind, the momentum outflow rate of which is

\[
\dot{P}_{\text{SMBH}} \approx \frac{L_{\text{Edd}}}{c} = \frac{4\pi GM_{\text{BH}}}{\kappa};
\]

here \( \kappa \) is the electron scattering opacity and \( M_{\text{BH}} \) is the SMBH mass. Because the cooling time of the shocked gas is short on scales appropriate for observed bulges, the bulk energy of the outflow is thermalised and quickly radiated away. It is then only the momentum push (equation 1) of the outflow on the ambient gas that is important since it is this that produces the outward force on the gas. The weight of the gas is \( W(R) = GM(R)[M_{\text{total}}(R)]^2/R^2 \), where \( M_{\text{gas}}(R) \) 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, \( M_{\text{gas}}(R) \) and \( M_{\text{total}}(R) \) are
proportional to $R$, so the result is

$$W = \frac{4f_g \sigma^4}{G}.$$  \hspace{1cm} (2)

Here $f_g$ is the baryonic fraction and $\sigma^2 = GM_{\text{total}}(R)/2R$ is the velocity dispersion in the bulge. By requiring that momentum output produced by the black hole just balances the weight of the gas, it follows that

$$M_\sigma = \frac{f_g \kappa}{\pi G^2} \sigma^4,$$  \hspace{1cm} (3)

which is consistent with the observed the $M_{\text{BH}}-\sigma$ relation.

McLaughlin et al. (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 IMFs produce momentum outflow rate

$$\dot{\Pi}_{\text{NC}} \approx \lambda L_{\text{Edd}}/c$$  \hspace{1cm} (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 a SMBH radiating at the Eddington limit, and hence:

$$M_{\text{NC}} = \frac{f_g \kappa}{\lambda \pi G^2} \sigma^4.$$  \hspace{1cm} (5)

Strikingly, $1/\lambda$ is quite close to the offset in mass between the $M_{\text{BH}}-\sigma$ and $M_{\text{NC}}-\sigma$ relations.

Nayakshin et al. (2009b) noted that timescales are important in this problem as well as energetics. SMBH growth is limited by the Eddington accretion rate, $M_{\text{Edd}} = L_{\text{Edd}}/(\epsilon c^2)$, where $\epsilon \sim 0.1$ is the radiative efficiency of accretion. SMBH masses can grow no faster than $\exp(t/t_{\text{Salp}})$, where

$$t_{\text{Salp}} = \frac{M_{\text{BH}}}{M_{\text{Edd}}} \times \frac{k \epsilon c}{4\pi G} = 4.5 \times 10^7 \epsilon_0.1 \text{ yr}$$  \hspace{1cm} (6)

is the Salpeter time, with $\epsilon_0.1 = \epsilon/0.1$. Star formation can occur on the free–fall or dynamical timescale $t_{\text{dyn}}$ of the system, which is less than a million years for many observed young star clusters. Nayakshin et al. (2009b) obtained for the dynamical time as a function of velocity dispersion:

$$t_{\text{dyn}} = 17 \left( \frac{\sigma}{150 \text{ km s}^{-1}} \right)^{2.06} \text{ Myr}$$  \hspace{1cm} (7)

A simple theory for the observed bimodality of NC and SMBHs was offered. In galaxies with small velocity dispersions ($\sigma \lesssim 150$ km s$^{-1}$), star formation occurs more rapidly than SMBH growth. NCs reach their maximum mass and drive the gas away before the hole can grow. The opposite occurs in galaxies with larger velocity dispersions, where SMBH are able to grow quickly enough to reach their maximum ($M_{\text{BH}}-\sigma$) mass. Low–dispersion bulges thus have underweight SMBHs, while high–dispersion bulges do not have nuclear star clusters.
2. Numerical models

One would clearly like to test these attractively simple explanations with careful numerical models of SMBH/NCs growth and feedback on the host. We have recently implemented a novel feedback and gas accretion model for SMBH (Nayakshin et al. 2009a, Nayakshin & Power 2010). SMBH wind outflows are modelled with collisionless "momentum particles", whereas accretion model follows the "sink particle" approach from star formation. In contrast to the Bondi-Hoyle models, our model obeys the angular momentum conservation law, e.g., accretes only low angular momentum gas, allowing us to follow accretion (Hobbs et al. 2010) and feedback in cases when discs form.

Simulating accretion on the SMBH and its feedback on gaseous shells in a static isothermal potential, Nayakshin & Power (2010) shows that the spherically symmetric initial conditions reproduce the King (2003, 2005) results excellently. However, when rotation or SMBH flow collimation are added to the initial conditions, the results get considerably more complicated, to the point that it is not clear how any robust $M_{\text{cmo}} - \sigma$ relation can be established. We emphasise that this is a completely general problem common to any realistic feedback model, as rotation or other symmetry breaking changes the one-to-one relation between accretion and feedback of the simple spherical models.

The following simulation of a collimated SMBH outflow misaligned with the disc demonstrates the general problem here. The simulation starts with a spherical rotating shell of gas far from the SMBH. For simplicity, the SMBH momentum outflow rate is fixed at the Eddington rate as described in the previous section. The outflow is constrained to the conical surface with opening angle $\theta = 45^\circ$ around the direction of the axis of symmetry of the outflow. The latter is inclined by angle $\pi/4$ from the $z$-axis defined by the direction of the angular momentum vector of the shell. For convenience of presentation, we choose the angular momentum vector of the shell and the outflow symmetry axis to lie in the $z-y$ plane.

Figure 1 shows projections of the gas surface density at times $t = 160$ Myrs (left panel) and $t = 400$ Myrs (right panel). While the gas dynamics is very complex, one thing is clear: collimated feedback leads to the separation of the gas into disc and outflow regions. While gas is driven off to infinity along the axis of the outflow, perpendicular to the axis, where there is no direct feedback, gas is able to accrete on the SMBH.

Summarising, more realistic models with rotation and/or anisotropic feedback allow SMBHs to feed via a disc or regions not exposed to SMBH winds. In these more realistic cases it is not clear why a robust $M_{\text{bh}} - \sigma$ relation should be established. In fact, some of the model predictions contradict observations. For example, an isotropic SMBH wind impacting on a disc (rather than a shell) of aspect ratio $H/R \ll 1$ requires the SMBH mass to be larger by a factor $\sim R/H$, which is opposite to what is observed (Honda 2009). In aspherical cases the SMBH outflows induce differential motions in the bulge. This may pump turbulence that is known to hinder star formation in star forming regions. SMBH feedback thus may not only drive gas out of the bulge but also reduce the fraction of gas turned into stars.
Figure 1. Angle-slice projected densities for the misaligned simulation at times $t = 160$ (left panel) and $t = 400$ (right panel) Myrs. The outflow eventually evacuates the directions along which it acts; only the inclined part of the disc that is shielded from the feedback survives to late times.

3. Conclusions

A further progress in understanding of feedback requires careful, physics-based, models of both accretion of gas and the effects that SMBH/NCs produce on their environment through energy and momentum deposition.

Acknowledgments. The author thanks Alex Hobbs and Andrew King for fruitful discussions on interstellar gas turbulence and AGN feeding.

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