How accreting black holes may shape their surroundings through AGN feedback

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Abstract

Black holes in active galactic nuclei (AGN) respond to the accretion process by feeding back energy and momentum into the surroundings. Such AGN feedback is generally invoked to quench star formation in host galaxies, either by heating or removing the ambient gas. However, feedback from the accreting black hole may also play other roles in galaxy evolution. We consider the role of radiation pressure on dust in driving outflows on galactic scales, and the possibility of AGN feedback triggering star formation within those feedback-driven outflows. In this picture, the accreting black hole is responsible for both driving star formation in the galaxy ('positive feedback'), as well as clearing dusty gas out of the host ('negative feedback'). I will discuss how the central black hole may shape not only the development of its own host galaxy, but also the evolution of the whole surrounding environment.

1 Introduction

Accreting black holes in galactic nuclei release huge amounts of energy and momentum into the surroundings via radiation, winds, and jets. Such active galactic nucleus (AGN) feedback is believed to play a key role in the formation and evolution of galaxies (Silk & Rees 1998, Fabian 1999, King 2003, see Fabian 2012 and references therein). Indeed, as the accretion energy released by the black hole clearly exceeds the binding energy of the galaxy bulge, AGN feedback must have a strong impact on its host galaxy. The basic question is to understand how the energy and momentum released by the accreting black hole actually couple to the surrounding medium.

On the observational side, there is now increasing evidence for powerful outflows on galactic scales. The outflows are observed to extend on ~kpc-scales and are typically characterised by high velocities (~ 1000km/s) and large momentum ratios (~ 10) (Veilleux et al. 2013, Cicone et al. 2014). Such powerful outflows are potentially able to clear out the entire galaxy, and have been posited as a proof of AGN feedback in action. However, the underlying physical mechanism powering the observed outflows is still a matter of great debate: is it a nuclear starburst or a central AGN? Is it energy-driving or radiation-driving? (e.g. Zubovas & King 2012, Thompson et al. 2015)

2 AGN feedback: radiation pressure on dust

We consider AGN feedback driven by radiation pressure on dust. As the dust absorption cross section is much larger than the Thomson cross section, the radiation-matter coupling can be much stronger. We assume that radiation pressure on dusty gas sweeps up the surrounding material into an outflowing shell. The general form of the equation of motions is given by (cf Thompson et al. 2015, Ishibashi & Fabian 2015):

$$\frac{d}{dt}(M_{sh}(r)v) = \frac{L}{c}(1 + \tau_{IR} - e^{-\tau_{UV}}) - \frac{GM(r)M_{sh}(r)}{r^2} \tag{1}$$

where L is the central luminosity, $M(r)$ the total mass distribution, and $M_{sh}(r)$ the shell mass.

The infrared (IR) and ultraviolet (UV) optical depths are respectively given by: $\tau_{IR}(r) = \frac{\kappa_{IR} M_{sh}(r)}{4\pi r^2}$ and $\tau_{UV}(r) = \frac{\kappa_{UV} M_{sh}(r)}{4\pi r^2}$. We note that there are three distinct physical regimes depending on the optical depth of the medium: optically thick to both IR and UV, optically thick to UV but optically thin to IR (single scattering), and optically thin to UV. The important point is that the momentum flux transferred from the radiation field to the gas is L/c in the single scattering limit, while it is boosted by a factor $(1 + \tau_{IR})$, if the medium is optically thick to the reprocessed IR radiation.

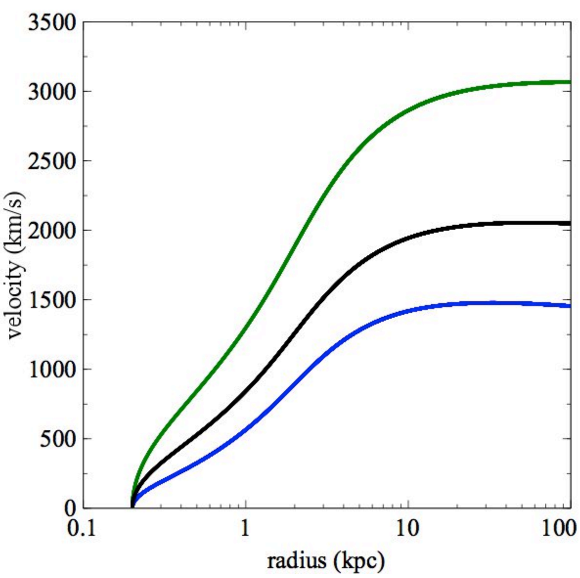

Figure 1: Velocity as a function of radius for variations in luminosity: $L = 3 \times 10^{46}$erg/s (blue), $L = 5 \times 10^{46}$erg/s (black), $L = 10^{47}$erg/s (green).

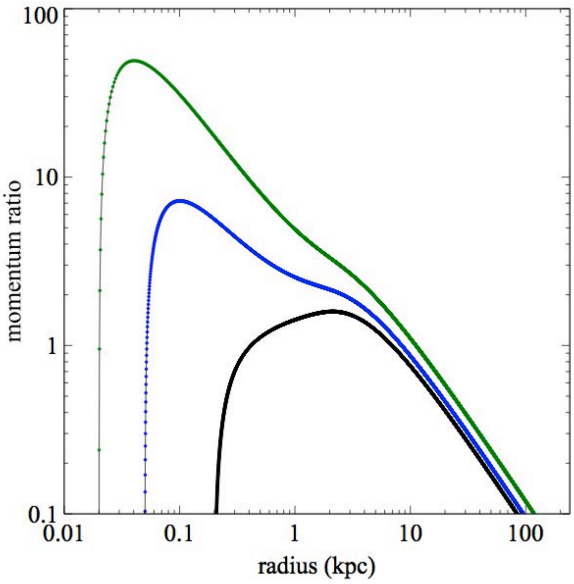

Figure 2: Momentum ratio as a function of radius for variations in initial radius: $R_0 = 200$ pc (black), $R_0 = 50$ pc (blue), $R_0 = 20$ pc (green).

Figure 1 shows the radial velocity profile of the outflowing shell obtained by integrating the equation of motion. We see that the shell can reach high velocities, of the order of $\sim$1000 km/s on $\sim$kpc scales. In Figure 2, we plot the momentum ratio of the shell, defined as $\zeta = \frac{\dot{M}v}{L/c} = \frac{M_{sh}v^2}{r\frac{L}{c}}$, as a function of radius. We observe that large values of the momentum ratio can be obtained for large initial IR optical depth, which can be due either to an enhanced IR opacity or a smaller initial radius. Therefore, taking into account the effects of radiation trapping, we can obtain outflowing shells with high velocities and large momentum flux, consistent with the observed outflows (Ishibashi & Fabian 2015).

Alternatively, the observed outflow characteristics may be significantly biased by AGN variability. In particular, the inferred momentum ratio can be over-estimated if the central AGN luminosity has declined over time (see Figures 3 and 4). This has interesting implications on the outflow driving mechanism, attributed to AGN- or starburst-driving. In some cases, powerful outflows observed on galactic scales, with no sign of ongoing nuclear activity and thus attributed to starbursts, may be re-interpreted as relics of past AGN activity (Ishibashi & Fabian 2015).

3 AGN feedback-triggered star formation

We have previously explored the possibility of AGN feedback triggering star formation in the host galaxy (Ishibashi & Fabian 2012). The squeezing and compression of the ambient medium (induced by the passage of the radiation pressure-driven outflow) may trigger local density enhancements, which in turn may lead to the triggering of star formation within the outflowing shell. Provided that the initial velocity is lower than the local escape velocity, the newly formed stars will remain bound to the galaxy. In this picture, new stars are successively formed at increasingly larger radii, leading to a gradual build-up of the outer envelope of the host galaxy.

This particular form of galaxy growth, induced by AGN feedback-driven star formation, may

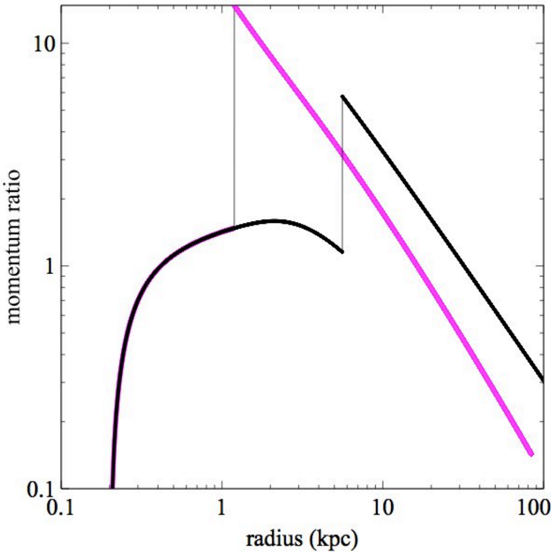

Figure 3: Momentum ratio as a function of radius in the case of a sudden drop in luminosity: $L_1 = 5 \times 10^{46}$erg/s, $L_2 = 1 \times 10^{46}$erg/s, $t_b = 5 \times 10^6$yr (black); $L_1 = 5 \times 10^{46}$erg/s, $L_2 = 5 \times 10^{45}$erg/s, $t_b = 2 \times 10^6$yr (magenta).

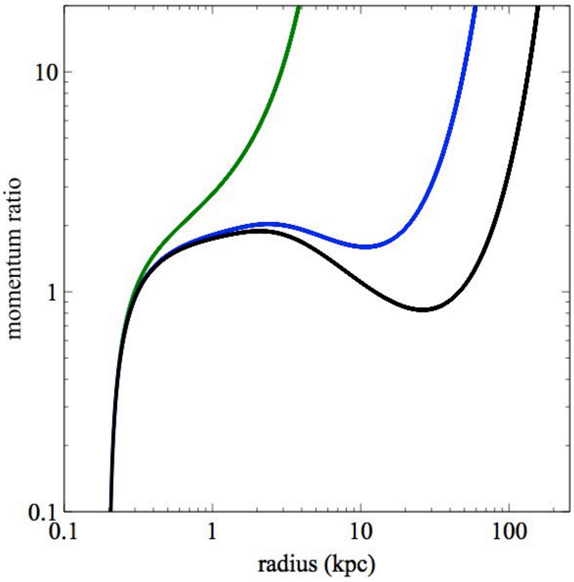

Figure 4: Momentum ratio as a function of radius in the case of an exponential decay in luminosity: $L_0 = 10^{47}$erg/s, $t_c = 10^7$yr (black), $t_c = 5 \times 10^6$yr (blue), $t_c = 10^6$yr (green).

contribute to explain the size evolution of massive galaxies observed over cosmic time (the so-called 'inside-out' growth pattern, van Dokkum et al. 2010).

A critical radius can be defined beyond which the outflow becomes optically thin to the central radiation:

$$R_c \sim \frac{\kappa f_g \sigma^2}{2\pi G} \tag{2}$$

This sets a physical boundary and an upper limit to the characteristic size of galaxies. The mass enclosed within the critical radius (assuming an isothermal distribution) is: $M_c(R_c) \sim \frac{2\sigma^2}{G} R_c \sim \frac{f_g \kappa_d \sigma^4}{\pi G^2}$, which corresponds to the galaxy mass obtained by considering the effective Eddington limit for dust.

Combining our predicted scaling of the critical radius with the standard $M_{BH} - \sigma$ relation, we obtain a relation between characteristic radius and mass of the form: $R \propto M^{1/2}$ (Ishibashi & Fabian 2014). Interestingly, this corresponds to the observed mass-radius relation of early-type galaxies (e.g. Shen et al. 2003, Newman et al. 2012). Therefore, the global properties of galaxies, such as characteristic radius and mass, could be essentially set by the action of radiation pressure on dust.

4 The different roles of AGN feedback

AGN feedback is most generally invoked to quench star formation in the host galaxy, either by removing or heating the ambient gas in the radiative and kinetic modes, respectively. This is the most commonly adopted 'negative feedback' paradigm, which has been implemented in various numerical simulations (e.g. Springel et al. 2005, di Matteo et al. 2005). However, feedback from the central black hole may also play other roles in galaxy evolution. In fact, we have seen that there are variety of ways in which the central black hole may affect its host galaxy, and not simply by quenching star formation as usually assumed in the standard negative feedback scenario.

In our picture, the accreting black hole is responsible for initially triggering star formation in the host galaxy (positive feedback), while eventually radiation pressure will clear the remaining dusty gas out of the host (negative feedback). Therefore the connection between the central black hole and its host galaxy is likely to be much more complex than previously thought and usually assumed. In this context, it is also interesting to note that 'mixed' scenarios involving both forms of positive and negative feedback have been recently debated in the literature (e.g. Silk 2013).

AGN-driven dusty outflows can also propagate beyond the host galaxy, and may contribute to the observed circum-galactic medium (CGM). In particular, the preferential ejection of dusty gas in the AGN-driven outflows may naturally account for the presence of dust and metals found in the CGM. Therefore, radiative-mode feedback may be equally important in shaping the large-scale environment of galaxies.

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