Two-phase model for black hole feeding and feedback

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ABSTRACT

We study effects of active galactic nucleus (AGN) feedback outflows on multiphase inter stellar medium (ISM) of the host galaxy. We argue that supermassive black hole (SMBH) growth is dominated by accretion of dense cold clumps and filaments. AGN feedback outflows overtake the cold medium, compress it, and trigger a powerful starburst – a positive AGN feedback. This predicts a statistical correlation between AGN luminosity and star formation rate at high luminosities. Most of the outflow's kinetic energy escapes from the bulge via low-density voids. The cold phase is pushed outward only by the ram pressure (momentum) of the outflow. The combination of the negative and positive forms of AGN feedback leads to an $M-\sigma$ relation similar to the result of King. Due to porosity of cold ISM in the bulge, SMBH influence on the low density medium of the host galaxy is significant even for SMBH well below the $M-\sigma$ mass. The role of SMBH feedback in our model evolves in space and time with the ISM structure. In the early gas rich phase, SMBH accelerates star formation in the bulge. During later gas poor (red-and-dead) phases, SMBH feedback is mostly negative everywhere due to scarcity of the cold ISM.

Key words: accretion, accretion discs – black hole physics – stars: formation – galaxies: evolution – quasars: general.

1 INTRODUCTION

We first review the current state of the analytical active galactic nucleus (AGN) feedback models in Section 1.1, and their relation to the observations. We then discuss two important challenges to these models that arose recently from microphysics of shocks, observations and numerical simulations in Sections 1.2 and 1.3. The scope of this paper and a brief description of the solution to these challenges are discussed in Section 1.5.

1.1 Spherically symmetric models of AGN feedback

1.1.1 Observations and energy-driven feedback

The mass M_{bh} of supermassive black holes (SMBH) residing in the centres of many galaxies is observed to correlate strongly with properties of the host. For example, $M_{bh} \simeq 1.5 \times 10^8 \sigma_{200}^4 \, \mathrm{M_\odot}$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000), where $\sigma_{200} = \sigma/200 \, \mathrm{km \, s^{-1}}$ and σ is the one-dimensional velocity dispersion of the stars in the host, $\sigma = (GM_{bulge}/2R_b)^{1/2}$, where M_{bulge} and R_b are the bulge mass and the effective radius, respectively. Furthermore, $M_{bh} \simeq 1.6 \times 10^{-3}M_{bulge}$ (Häring & Rix 2004), although a more recent census of *classical* bulge systems show a higher M_{bh}/M_{bulge} ratio by a factor of a few (Kormendy & Ho

2013). More recent observations show correlations of M_{bh} with other properties of the host (Graham 2004; Ferrarese et al. 2006; Cattaneo et al. 2009). Barred galaxies show underweight black holes (Graham 2008; Hu 2008; Kormendy, Bender & Cornell 2011), possibly indicating that SMBH growth is fuelled not by planar inflows but rather by a 'direct' deposition of cold clouds from the bulge (Nayakshin, Power & King 2012).

Pre-dating these observations, Silk & Rees (1998) envisioned that SMBH may influence their host galaxies strongly despite being a tiny fraction of the total mass. They showed that *energy-conserving* outflows from growing SMBH could expel all the gas in the host galaxy, terminating SMBH and galaxy growth. This model assumes that primary outflow from the SMBH does not cool when shocked in the interaction with the ambient gas. Quantitatively, however, the theory predicts $M_{bh} \propto \sigma^5$ and requires a surprisingly inefficient coupling between the power output of SMBH and the host. Let us write the energy passed from the outflow to the gas in the host as $\epsilon_e M_{bh}c^2$. Requiring $\epsilon_e M_{bh}c^2 \sim f_g M_{bulge}\sigma^2$, and $f_g \sim 0.1$ is the fractional mass of the gas in the bulge, we find that $\epsilon_e \sim 5 \times 10^{-5}$ to yield $M_{bh} \sim 10^{-3}M_{bulge}$ at $\sigma = 200 \, \mathrm{km \, s^{-1}}$. Such inefficiency is puzzling. For comparison, the radiative power output of SMBH gives efficiency of the order of $\epsilon_r \sim 0.1$ (Shakura & Sunyaev 1973). In fact, the recent study of Kormendy & Ho (2013) excluded pseudo-bulges and systems currently undergoing mergers from the sample, focusing only on the classical bulges, and obtained the SMBH to bulge mass ratio of ~ 0.005 rather than ~ 0.0015 favoured by earlier studies. This further lowers the estimate of the energy coupling

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between the UFO and the bulge to $\epsilon_e \sim 2 \times 10^{-5}$. In contrast, numerical simulations reproducing the observed correlations require efficiencies of the order of $\epsilon_e \sim 5 \times 10^{-3}$ (Di Matteo, Springel & Hernquist 2005).

Concluding, it appears that energy-driven feedback models simply produce too much energy in the outflow; these models must invoke, somewhat arbitrarily, a tiny energy coupling factor to the bulge, $\epsilon_e \sim (2-5) \times 10^{-5}$. It is not clear why this factor would be constant from one galaxy to another, and therefore why a tight correlation between M_{bh} and M_{bulge} (Kormendy & Ho 2013) would exist at all in this framework.

1.1.2 Successes of momentum and energy-driven model

King (2003) proposed a more detailed AGN feedback model which is able to account naturally for most of the relevant observations to date. In this model, SMBH outflows start from the innermost region of the accretion discs, and escape the region at velocity comparable to the local escape velocity, e.g. $v_{out} \sim 0.1c$. Such outflows were actually observed in quasar PG 1211+143 (King & Pounds 2003; Pounds et al. 2003). The outflows carry a momentum flux $\dot{M}v_{out} \sim L_{Edd}/c$, comparable to the escaping radiation momentum flux when the SMBH luminosity is at the Eddington limit, L_{Edd}. Pleasingly, the kinetic energy carried by the ultrafast outflow (UFO) is $(v_{out}/2c)L_{Edd}$, which is equivalent to $\epsilon \sim 5 \times 10^{-3}$, naturally accounting for the empirical results of Di Matteo et al. (2005). Furthermore, observational support for widespread existence of and a significant power carried by the UFOs has since become available (e.g. Tombesi et al. 2010a,b; Pounds & Vaughan 2011).

The key characteristic of this model is that it operates in both momentum-conserving and energy-conserving regimes at different times. King (2003) has shown that close to the SMBH, shocked UFO wind suffers significant Inverse Compton (IC) losses on the AGN radiation field. Equalling the IC cooling time to the flow time, one finds the IC cooling radius, $R_{ic} \sim 0.5 \,\mathrm{kpc}\, M_8^{1/2} \sigma_{200}$, where $M_8 = M_{bh}/10^8 \,\mathrm{M_\odot}$ (King, Zubovas & Power 2011). The outflow is losing most of its kinetic energy, $(1/2)\dot{M}v_{out}^2$, within $R \lesssim R_{ic}$, and is in the momentum-conserving regime. The ambient gas in this regime is affected mainly by the physical push from the UFO. Considering the equation of motion for the swept up ambient gas shell, King (2003) derived the maximum SMBH mass, called M_σ mass, above which the outflow from it clears the galaxy of the ambient gas.

We retrace the steps in this derivation in a simpler order of magnitude approach, only considering the force balance between the momentum outflow rate and the gravity of the ambient swept-up shell. The structure of the ambient gas in this model follows that in a singular isothermal sphere potential (e.g. section 4.3.3b in Binney & Tremaine 2008) for simplicity. For such a potential, the one-dimensional velocity dispersion is a constant independent of radius, $\sigma = (GM_{total}/2R)^{1/2}$, where $M_{total}(R)$ is the total enclosed mass including dark matter inside radius R (the distance from the centre of the galaxy). The enclosed gas mass, $M_g(R) = f_g M_{total}(R) = 2f_g \sigma^2 R/G$ is proportional to R. The gas density at radius R for such a potential is

$$\rho_g(R) = \frac{f_g \sigma^2}{2\pi G R^2} \equiv f_g \rho_0(R) \,, \tag{1}$$

where we defined the total potential density, $\rho_0(R)$ for convenience; f_g is the baryon fraction. Note that the initial cosmological value of f_g is $\simeq 0.16$ (cf. Spergel 2007). Requiring the weight of the swept-

up shell at radius R, $W(R) = GM(R)[M_{total}(R)]/R^2 = 4f_g\sigma^4/G$, to be equal to the momentum flux from the AGN,

$$W(R) = \frac{L_{Edd}}{c} = \frac{4\pi G M_{bh}}{\kappa} \,, \tag{2}$$

one arrives at

$$M_{bh} = M_\sigma = f_g \frac{\kappa \sigma^4}{\pi G^2} \approx 3.6 \times 10^8 \,\mathrm{M_\odot}\, \frac{f_g}{0.16} \,\sigma_{200}^4 \,. \tag{3}$$

This is very close to the observed relation (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Kormendy & Ho 2013).

In this model, once M_{bh} exceeds M_σ, the ambient gas is pushed further out. The outflow accelerates once the shock expands to $R \gtrsim R_{ic}$, because at that point IC losses become less important and the outflow switches over into the energy-conserving regime. This feature of the model is essential to explaining how the UFOs, initially momentum driven, can then deliver a much larger push to the ambient gas in the host (King 2005, 2010). The outflow velocity of the ambient cold gas accelerated by the UFOs in the energy-driven regime in fact reach $\sim 1000 \,\mathrm{km\,s^{-1}}$, and the mass outflow rates as large as $10^3 \,\mathrm{M_\odot \,yr^{-1}}$, consistent with recent observations (e.g. Feruglio et al. 2010; Rupke & Veilleux 2011; Sturm et al. 2011). This energy-driving boost present in the King (2003) model also naturally accounts for the need to boost the momentum output of the SMBH by a factor of several over the pure momentum-driven limit as found by Silk & Nusser (2010).

Applying similar momentum-conserving outflow logic to stellar outflows from young massive stellar clusters, one can account for both the observed $M_{bh}-\sigma$ relation for Nuclear star Clusters (see McLaughlin, King & Nayakshin 2006) and the observation that NCs are preferentially found in low-mass (low σ) galaxies (Nayakshin, Wilkinson & King 2009). The model has been also used (Zubovas, King & Nayakshin 2011) to explain the two $\sim 10 \,\mathrm{kpc}$ scale bubbles in the Milky Way, emitting high-energy radiation, and thus presumably filled with cosmic rays (Su, Slatyer & Finkbeiner 2010). To explain the particular geometry of the bubbles, the only adjustment to the basic King (2003) model required by Zubovas et al. (2011); Zubovas & Nayakshin (2012) has been an addition of a dense disc of molecular gas, known as the Central Molecular Zone, found in the central $\sim 200 \,\mathrm{pc}$ of our Galaxy (Morris & Serabyn 1996).

1.2 Are shocks one or two temperature?

All of the AGN feedback models quoted above assumed a one-temperature model ('1T' hereafter) for the shocked gas, so that electrons and protons share the same temperature everywhere in the flow. This is a reasonable assumption for dense or relatively cold plasmas, since the electron–proton energy exchange rate due to Coulomb collisions is large in such conditions. However, when the plasma density becomes sufficiently low and/or ion temperature becomes larger than $T_i \gtrsim 10^9 \,\mathrm{K}$, the electrons and ions can thermally decouple from each other (Shapiro, Lightman & Eardley 1976).

Faucher-Giguère & Quataert (2012) showed that shocked UFOs may indeed be in this second, two-temperature ('2T' hereafter), regime. They found that for an outflow velocity of $0.1c$ and $L_{Edd} = 10^{46} \,\mathrm{erg\,s^{-1}}$, the ion temperature is as high as $T_i = 2.4 \times 10^{10} \,\mathrm{K}$ but the electron temperature reaches a maximum of $T_e \sim 3 \times 10^9 \,\mathrm{K}$ in the post-shock region. IC cooling for such 'cold' electrons is practically negligible, in the sense that R_{ic} becomes comparable to the SMBH influence radius, that is, a few parsec. These scales are tiny by the host galaxy's standards and are thus unimportant.

This 2T regime for the reverse shock may be of a key importance to the UFO-based theory of AGN feedback, since then the momentum-driven regime would disappear (and the M_σ mass given by equation 3) and we would be back to the energy-driven paradigm. Since $\epsilon_e \sim 0.005$ in this model, we would expect SMBH mass to be only $\sim 10^{-5} M_{bulge}$, a factor of a few hundred below what is actually observed. This is therefore a significant logical problem.

The result of Faucher-Giguère & Quataert (2012) is not a foregone conclusion. Although observations of fast astrophysical shocks and theoretical work (see section 2.2 for references in Faucher-Giguère & Quataert 2012) favours the $T_e \ll T_i$ case, it is still not entirely ruled out that collective plasma physics effects transfer the energy between the charged species faster than Coulomb collisions (e.g. Quataert 1998) in the UFO setting.

However, there is now some observational support for the notion that $T_e \ll T_i$ in the reverse shocks of the UFOs. Bourne & Nayakshin (2013) proposed an observational test of whether the UFO shocks are radiative or not. They calculated the inverse Compton cooling cascade (ICCC) emission from the spherical shocks expected in the 1T model. The resulting spectrum in $2-10$ keV X-rays looks like a power law out to the roll-over energy of $\sim 50-200$ keV, depending on the outflow velocity and the shape of the optical–UV spectrum of the quasar. Bourne & Nayakshin (2013) compared this theoretical ICCC spectrum with typical spectra of AGN and argued that there is *currently* no evidence for the presence of ICCC component in the later. In particular, while the spectral shape is reasonably similar, a whole range of variability and spectral features such as a broad Fe Kα, and evidence for sub-pc scale X-ray obscuration sets the ICCC spectra apart from what is actually observed.

The results of BN13a are suggestive that the reverse shock of the UFO is in the 2T regime but not entirely conclusive for the following reasons. It is possible that AGN with powerful enough outflows, e.g. those in which the kinetic power of the outflow is the assumed 5 per cent fraction of the bolometric luminosity of the AGN, are rare, and future observations will discover the 'missing' ICCC component. The second possible interpretation is that the geometry of the shock is far from spherical and therefore the expected ICCC emission is strongly diluted. In particular, in the two-phase picture of the ambient inter stellar medium (ISM) that we are advocating here, most of the solid angles as seen from the SMBH is filled with a hot tenuous ISM. We shall argue that this component is driven away rapidly no matter whether the reverse shock is 1T or 2T. Most of the UFO may thus shock at radii larger than even the 1T cooling radius and therefore be in the energy-conserving regime. This would reduce the expected ICCC signature perhaps below detectability.

Accordingly, in this paper we assume that UFO reverse shocks are in the energy-conserving regime everywhere for simplicity, except within the cooling radius that is typically just a few pc in the 2T case (Faucher-Giguère & Quataert 2012), a region that we neglect in our galaxy-wide study. Our main results are unchanged if UFO reverse shock is actually 1T and cools efficiently within a small fraction of the bulge.

1.3 Multiphase ambient gas

Recent well-resolved 3D simulations of AGN feedback by Nayakshin & Zubovas (2012) and Zubovas et al. (2013b) show that the forward shock driven into the ambient gas is unstable to a variant of Raleigh–Taylor instability, provided the outer shock cooling time is short. The instability is physically similar to the 'Vishniac instability' previously known in the context of supernova remnant studies
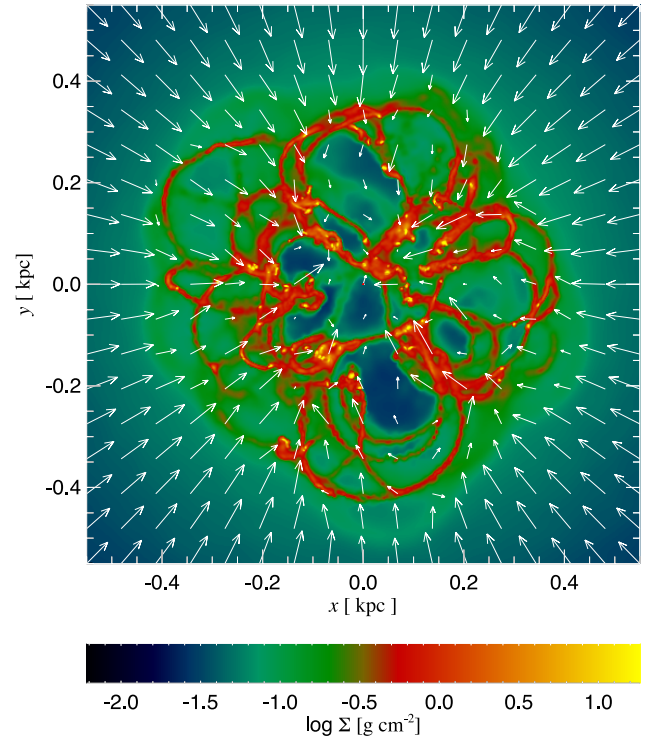

Figure 1. Projected column density (colours; the scale bar is on the bottom of the figure) and velocity vectors of the gas for a simulation of AGN feedback described in the text. Note the dense filaments and clumps that are infalling on to the SMBH.

(Vishniac 1983; Mac Low, McCray & Norman 1989). Nayakshin & Zubovas (2012) find that the compressed outer shell breaks into filaments and massive dense clumps on the intersection of the filaments. For $M_{bh} \lesssim M_\sigma$, e.g. when the shocked shell stalls and re-collapse on the SMBH, the dense filaments collapse fastest on to the SMBH. Physically, the filaments experience a much smaller outward acceleration due to the outflow because they have a very large column depth compared with the mean for the shell.

Fig. 1 presents the gas column density and velocity field for the simulation presented in Nayakshin & Zubovas (2012). The SMBH mass in this simulation is $M_{bh} = 10^8$ M$_\odot$, which is ~ 30 per cent below a numerically found $M-\sigma$ mass for the setup (see the simulations in Zubovas et al. (2013b) that show $M_{bh} > M_\sigma$ cases for the same potential). The densest parts of the shell eventually collapse on to the black hole in this simulation, while the lower density 'bubbles' grow larger than in Fig. 1.

This figure demonstrates very clearly that validity of the spherically symmetric shell approximation for AGN feedback in a situation such as obtained here must break down. We would like to emphasize that the simulations of Nayakshin & Zubovas (2012) and Zubovas et al. (2013b) were started from spherically symmetric initial conditions. This is why the gas outside the inner ~ 0.4 kpc is uniform in Fig. 1. Gas in realistic galaxies is expected to be multiphase even without AGN feedback, as soon as the radiative cooling time in the bulge is comparable to the dynamical time (McKee & Ostriker 1977; Fall & Rees 1985). 3D numerical simulations clearly show that thermal instabilities in the gas lead to a cooling runaway in denser regions; these regions not only become cooler but are also further compressed by the virialized surrounding hot gas (e.g. Barai, Proga & Nagamine 2012; Hopkins, Quataert & Murray 2012; Gaspari, Ruszkowski & Oh 2013; Mościbrodzka & Proga 2013).

Such thermal instabilities and/or turbulence induced by supernova explosions in the bulge are likely to lead to the chaotic AGN accretion mode in which dense filaments stream ballistically into the central parsecs of the host (e.g. Hobbs et al. 2011).

Besides testing the validity of the spherically symmetric models, simulations such as that presented in Fig. 1 also indicate an important new physical effect of AGN feedback on its host: triggered star formation in the cold dense gas caused by the extremely high pressure of the UFO shocks (e.g. Nayakshin & Zubovas 2012; Silk 2013; Zubovas et al. 2013a,b). Such a positive AGN feedback was also invoked by Silk & Nusser (2010) to provide for extra feedback within the bulge.

Finally, observations of AGN-driven molecular outflows constrain mean density and the total mass of molecular gas in the host, which then implies that the gas must reside in dense clumps (e.g. Aalto et al. 2012; Cicone et al. 2012), as envisioned above.

1.4 The role of galactic discs

Our model posits that most of SMBH growth occurs due to accretion of cold clumps or filaments from a quasi-spherical bulge of the galaxy. As discussed above, hot gas from the bulge does not contribute to SMBH growth significantly unless it cools and switches phases. The other likely and significant reservoir of cold gas is a galactic disc which must form inevitably if there is sufficient angular momentum in the host galaxy. This disc could in principle fuel SMBH growth instead of the cold clumps, but we argue that galaxy-scale discs do not transfer angular momentum sufficiently rapidly to provide the dominant source of AGN feeding.

On the theory side, this view is supported by the fact that AGN accretion discs are unstable to self-gravitational instability beyond ∼0.1 pc; it is hard to see how such discs could fuel AGN (e.g. Goodman 2003; Nayakshin & King 2007) for tens of millions of years, the likely duration of SMBH growth phase.

Observations also disfavour large discs (or bar) as the dominant sources for SMBH growth. The view developing observationally is that bright quasars reside in classical bulges or elliptical galaxies, whereas galaxies dominated by discs host AGN that are typically dimmer by one to two orders of magnitude (Kormendy & Ho 2013).

Furthermore, these SMBH feeding-based objections against disc-dominated growth of SMBH can be also backed up from the AGN feedback angle. Nayakshin et al. (2012) showed that if galactic scale disc were able to self-regulate their star formation rate due to stellar feedback within the discs, as argued by Thompson, Quataert & Murray (2005), and thus feed the SMBH efficiently, then one would expect SMBH in galaxies with prominent discs or bars to be a factor of a few to 10 more massive than SMBH in elliptical galaxies at same velocity dispersion. This conclusion stems from a simple geometric argument: most of AGN feedback misses the disc. It is thus very hard to stop SMBH growth via a disc or a bar *if* those processes were efficient if feeding the SMBH. Observations of pseudo-bulge systems show the opposite result: SMBH in such galaxies are underweight with respect to their cousins in classical bulges by a factor of a few to 10 (Hu 2008; Graham 2008), and in fact may not even correlate with σ (Kormendy et al. 2011; Kormendy & Ho 2013).

The final problem with a planar mode of SMBH feeding is pointed out by Zubovas et al. (2013a), who showed that pressure in the hot bubbles inflated by AGN feedback is much larger than the pressure in the self-regulated galactic discs studied by Thompson et al. (2005). These discs are thus overpressured by the bubbles into much more rapid star formation than on its own. This speeds up their transformation into stellar rather than gaseous discs and makes SMBH feeding even harder.

For these reasons, galactic discs do not feature in our paper. They are important engines for formation of galactic stellar discs and transfer of matter on kpc-scales, but we see no theoretical or observational basis to connect such discs to *most* of SMBH growth.

1.5 The scope and main results of the paper

We believe that the basic scenario for the AGN feedback proposed by King (2003) is the most promising of all the models available in the literature to date since it is based on robust physical expectations for near-Eddington AGN accretion flows and actual observations of UFOs, as described in Section 1.1. The goal of our paper is to ask how this model should be modified when one takes into account a number of the latest results in the field: (i) the 2T regime for the UFO reverse shock; (ii) the multiphase structure of the ambient and shocked ambient gas; (iii) AGN-triggered star formation in the host and (iv) chaotic AGN accretion.

We find that in a realistic two-phase environment, (a) cold ambient gas is driven outward by the outflow's momentum only (as in King (2003) model) despite the outflow being energy conserving, and (b) the hot/low-density phase is affected by both the energy and the momentum of the outflow, so being driven off much easier than the cold gas; (c) star formation in the densest clouds in the cold phase is essential in limiting SMBH growth. The implications of our results are reviewed in Section 3.

2 AGN FEEDBACK ON A MULTIPHASE AMBIENT GAS

2.1 The model and assumptions

We follow the model of King (2003) in that the SMBH produces a momentum flux during its Eddington-limited outburst of $L_{\rm Edd}/c$, and that the outflow velocity is $v_{\rm out} \sim 0.1c$. We also assume an isothermal galaxy potential dominated by dark matter, and a quasi-spherical distribution of ambient gas in the host. In variance to King (2003), however, we assume that the ambient medium consists of two phases – 'hot' and 'cold', as sketched in Fig. 2. The hot medium's temperature is about the virial temperature, $k_b T_{\rm hot}/\mu \approx GM_{\rm tot}/R = 2\sigma^2$, whereas the cold clouds are much cooler. The hot volume phase occupies most of the volume inside the host, while the cold medium probably carries most of the gaseous mass (McKee & Ostriker 1977; Fall & Rees 1985).

In Fig. 2, arrows indicate UFO from the SMBH which is located at the centre of the bulge of the host galaxy. We assume that the hot medium interacts with the UFO as found in the spherically uniform models (e.g. King 2010; Faucher-Giguère & Quataert 2012; Zubovas & King 2012), except the hot gas mass fraction (see below) may be lower and variable with radius. Counting from the SMBH, there are then three important surfaces where the nature of the flow changes discontinuously: the reverse shock, the contact discontinuity and the forward shock, all indicated in the figure. The cold medium however is able to 'penetrate' the shocks in the sense that the shocked outflowing material overtakes the cold clouds.

One of the points of our paper is to show that the momentum of the UFO is still key to establishing the $M-\sigma$ relation even if the outflow is always in the energy-driven regime, as suggested by the results of Faucher-Giguère & Quataert (2012). We therefore assume that the outflow is in the energy-conserving mode everywhere.
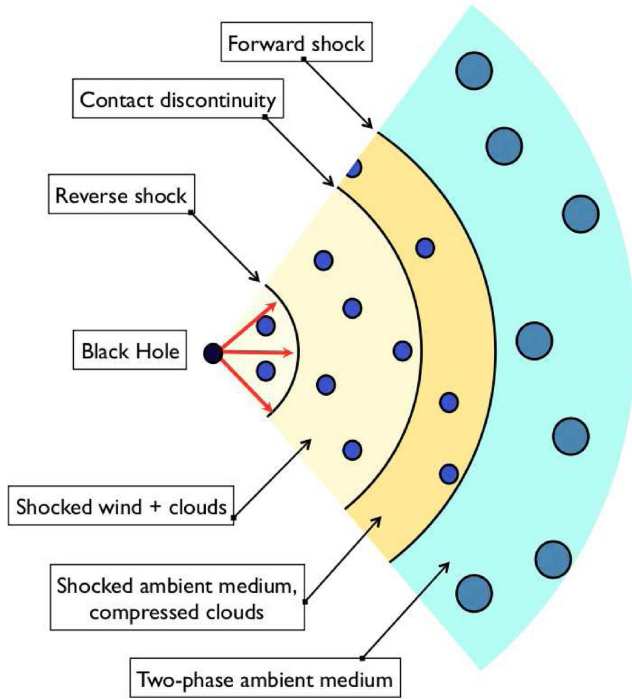
Figure 2. Sketch of the geometry of the problem. The black hole is at the centre of a quasi-spherical host bulge. Ambient gas in the host consists of a low-density hot medium enveloping a cold high-density clouds. The UFO from the AGN shocks mainly against the hot low-density gas, driving an energy-driven flow out to great distances. The cold dense clouds are pushed outward just by the ram pressure of the outflow but are also compressed by its high pressure and experience a triggered star formation bust. See the text in Section 2.1 for more detail.

2.2 The hot phase: energy driving

We argue that the density of the hot ambient medium is determined by the balance between virialization shocks and radiative cooling. This requires that the density of the hot gas is approximately that which gives radiative cooling time of the order of dynamical time (Fall & Rees 1985). Using the cooling function of Sutherland & Dopita (1993), we find

$$f_{\rm h} = \frac{\rho_{\rm h}}{\rho_0} \approx 2.5 \times 10^{-3} \sigma_{200}^{5/2} R_{\rm kpc} z^{-0.6} , \qquad (4)$$

where z is the metallicity of the gas in units of Solar metallicity, $R_{\rm kpc}$ is distance R in units of 1 kpc. This estimate would be somewhat higher if we also considered feedback from a likely ongoing star formation in the host, but even this does not change the main conclusion: $f_{\rm h}$ is quite small compared with the initial cosmological gas fraction $f_0 = 0.16$, so that most of the mass is expected to reside in the cold gas phase (also, cf. simulations by Hopkins et al. 2012).

The outflow interacts with the two phases differently. The outflow shocks against the hot medium and drives it outward in the energy-driven regime, as calculated by King (2003, 2010), Zubovas et al. (2011), except that the hot gas density fraction $f_{\rm h}$ is lower than f_0. Since the energy-driving regime is much more efficient than the momentum-driven one, and since $f_{\rm h}$ is small, the hot medium is expelled relatively easily. To appreciate our point, let us consider the binding energy of the hot component in the bulge, writing it by order of magnitude as $E_{\rm h} \sim M_{\rm h}\sigma^2 = f_{\rm h}M_{\rm bulge}\sigma^2$, where $M_{\rm h} = f_{\rm h}M_{\rm bulge}$ is the mass of the hot ISM in the bulge of mass $M_{\rm bulge}$. Compare

this energy to kinetic energy of the UFO emitted by the SMBH, $E_{\rm UFO} \sim 0.1\, M_{\rm bh}(v_{\rm out}^2/2)$:

$$\frac{E_{\rm h}}{E_{\rm UFO}} \sim 10^{-3}\, \frac{f_{\rm h}}{0.01}\, \sigma_{200}^2 . \qquad (5)$$

Here we used the observational fact that bulges are typically ~ 1000 times more massive than SMBH they host (Häring & Rix 2004). Since $f_{\rm h}$ is much smaller than unity and definitely cannot exceed unity by definition, we see that $E_{\rm h}/E_{\rm UFO} \ll 1$ always, and it thus must be an easy task for the UFO to remove the hot phase from the bulge.[1]

Furthermore, we note that SMBH is not likely to be fed directly by the hot-phase gas for at least two reasons. First of all, as is well known, hot gas overheats inside non-radiative accretion flows and gets unbound (Blandford & Begelman 1999); secondly, even if hot gas could fuel some AGN activity, its low density makes it very vulnerable to feedback outflows from AGN. Some of the well-known astrophysical examples of this behaviour are the SMBH in the nearby giant elliptical galaxy M87 (e.g. Di Matteo et al. 2003), Sgr A*, the SMBH in the centre of our Galaxy (Baganoff et al. 2003; Cuadra et al. 2006) and 'cooling flows' in galaxy clusters (Churazov et al. 2002).

Since we concluded that the hot ISM does not play a significant role in SMBH feeding and is blown away in the energy-conserving mode efficiently by UFOs, our thesis is that this phase plays no role in establishing the $M-\sigma$ relation.

2.3 The cold phase: momentum driving

In our model, similarly to the interaction of supernova blast waves with cold ambient clouds, the fast outflow from the AGN overtakes cold clouds rather than pushes them in front of itself (e.g. McKee & Cowie 1975). Lower density clouds are probably crashed and dispersed, with their gas joining the ambient hot shocked gas (thus increasing $f_{\rm h}$ from the estimate above). Higher density clouds however survive and lag behind the forward shock; they are eventually entrained in both the forward and the reverse shock regions.

We note that highest density clouds are much more resilient to AGN feedback and can be pulled inward by gravity even in the presence of an energetic outflow (cf. Fig. 1). For this reason, the SMBH is fed in our model by high-density clouds rather than by the 'mean' density ambient gas. We therefore envisage that cold phase permeates the host galaxy everywhere (see Fig. 2), although it fills a small fraction of the galaxy's volume.

To gain some analytical insight into this complicated problem, let us consider the cold phase to be a population of spherical clouds, each of mass m, spherical radius r and $\Sigma = m/(\pi r^2)$, the cloud's column density. The UFO shocks against the cloud, building up a bow shock in front of it (as in fig. 1 of McKee & Cowie 1975). Importantly, considering the radial motion of the cloud, we only need to include the momentum flux of the fast outflow directly impacting the cloud; while the fast outflow shocks in the bow shock region, the thermalized energy of the shock simply overflows the cloud sideways (McKee & Cowie 1975).

As in the King (2003) model, the SMBH outflow produces ram pressure (momentum flux) at distance R from the SMBH equal to

$$P_{\rm ram} = \frac{L_{\rm Edd}}{4\pi R^2 c} = \frac{G\, M_{\rm bh}}{R^2 \kappa} . \qquad (6)$$

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[1] Of course in reality smaller cold clouds are destroyed by the UFO shocks, and thus there is a continuous replenishment of the hot phase in the bulge.

The inward-directed gravitational force acting on the cloud is balanced by the ram pressure of the outflow when

$$\frac{GM_{\rm tot}(R)}{R^2}m \sim P_{\rm ram}\pi r^2 \ . \tag{7}$$

Outflow's ram pressure on the cloud exceeds gravitational force from the bulge if

$$M_{\rm bh} \gtrsim \frac{\kappa\sigma^4}{\pi G^2}\frac{\rho}{\rho_0}\frac{r}{R} \ . \tag{8}$$

However, we should also estimate the number of clouds on a line of sight, N_l, as seen from the SMBH. Trivial geometrical considerations show that this is of the order of $N_l \sim O(1)f_c\rho_0 R/(\rho r)$, where $f_c \equiv \rho_c/\rho_0$ is the volume-averaged cold gas mass fraction, equivalent to f_g in the model of King (2003), except that the latter encompasses all of the gas. Choosing $O(1) \sim 1$, we get the result formally correct in the case of smooth spherically symmetric cold medium (that is, if $f_h = 0$, we should have exactly one cold 'cloud' with density $\rho = f_c\rho_0$ and $r = R$ per line of sight), so we write

$$N_l \sim f_c \frac{\rho_0 R}{\rho r} \ . \tag{9}$$

We then require that in general the momentum flux from the SMBH must exceed the weight of $(1 + N_l)$ clouds. This is asymptotically correct in the corresponding opposite limits, $N_l \ll 1$ (when we need to consider only one cloud as other clouds do not shadow it), and $N_l \gg 1$. With this, the critical SMBH mass in our model is

$$M_{\rm bh} \sim \frac{\kappa\sigma^4}{\pi G^2}\left(f_c + \frac{\rho r}{\rho_0 R}\right) \ . \tag{10}$$

2.4 Star formation limiter and the $M-\sigma$ relation

In principle, clouds could be arbitrarily dense, $\rho \gg \rho_0$, which would make it all but impossible to stop them from falling in despite the ram pressure from the UFO. Formally, in this limit the column depth of the cold clouds, $\Sigma \sim \rho r$, could be arbitrarily high, so that for densest clouds $\Sigma \gg \rho_0 R$ and thus the last term in equation (10) becomes arbitrarily large. SMBH could then grow by accretion of such clouds to masses much larger than observed.

However, clouds that have very large densities and short cooling times are self-gravitating and are liable to fragmentation into stars. We argue that such clouds cannot feed the SMBH because the constituent gas is partially turned into stars, while the remainder of the cloud is disrupted (unbound) by star formation feedback (this is the fate of most Galactic star-forming molecular clouds, e.g. McKee & Ostriker 2007). In the presence of AGN outflow, the remnants of the star formation disrupted cloud are shocked, heated up and mixed with the AGN outflow.

Now consider conditions for a cloud to be self-gravitating: its self-gravity must exceed the tidal force from the bulge, so that

$$\frac{Gm\rho}{r^2} \sim \frac{GM_{\rm tot}}{R^2}\frac{r}{R} \ . \tag{11}$$

By the order of magnitude, we can conclude from the above that

$$\rho_{\rm sg} \sim \frac{\sigma^2}{2\pi GR^2} = \rho_0 \tag{12}$$

gives the mean density of a cloud that is just self-gravitating, where ρ_0 is the density of the background potential introduced by equation (1).

Therefore, the maximum density of gas clouds that fuel SMBH growth is limited by $\rho_{\rm sg} \sim \rho_0$ in our model. The radial size of the

clouds, r, depends on the cloud's mass m, but clearly cannot be larger than some small fraction of radius R. We thus introduce a parameter $\delta \equiv \rho r/(\rho_0 R) \ll 1$, averaged over the ensemble of cold clouds in the host. With this we write the critical 'cold' SMBH mass as

$$M_{\rm cold} \sim \frac{\kappa\sigma^4}{\pi G^2}(f_c + \delta) \ = \ 2.2 \times 10^8 \, {\rm M}_\odot \frac{f_c + \delta}{0.1}\sigma_{200}^4 \ . \tag{13}$$

This is the critical SMBH mass which should be compared to the observed $M-\sigma$ relation (e.g. Kormendy & Ho 2013).

3 DISCUSSION

Observations require a successful AGN feedback theory to operate in both the momentum-conserving regime – to explain the $M-\sigma$ relation and the low efficiency of AGN feedback coupling to the gas in the host, and in the energy-conserving regime to explain the massive molecular and ionized outflows observed (e.g. Feruglio et al. 2010; Rupke & Veilleux 2011; Sturm et al. 2011). In the spherically symmetric one-phase model (King 2003, 2005, 2010) these two regimes appear naturally. While SMBH is below the $M-\sigma$ mass, the outflow stalls and loses most of its energy by IC radiation in the central few hundred pc of the bulge, and is thus momentum driven in that region. Once $M_{\rm bh} > M_\sigma$, this clears the central region and it then switches over into the energy-conserving regime.

The two-phase model proposed here is similar to that of King (2003) in many regards. We use exactly same model for the UFO, which we believe is the main culprit of AGN feedback on the host. We also find the momentum-driven and the energy-driven regimes for the UFO interaction with the ambient medium. We derive an $M-\sigma$ mass that is formally similar to the one obtained by King (2003). However, there are also significant differences in the assumptions of the model: (a) most importantly, the ISM of the host galaxy is multiphase in our model and (b) we assume the reverse shock to be in 2T regime (see Faucher-Giguère & Quataert 2012), although our results are not very sensitive to this assumption, and will not change significantly if the electrons and ions have same temperature.

We now summarize key conclusions and results from this paper.

(1) Equation (13) gives an $M-\sigma$ relation for cold clouds exposed to AGN outflow carrying the momentum flux $L_{\rm Edd}/c$. It is similar to the result of King (2003), despite the fact that we assumed that UFOs are energy-conserving everywhere. Our result follows mainly from two conclusions – that cold dense clouds are overtaken by the UFOs, so experience only the momentum push, and that the density of the clouds that can feed the SMBH is limited by cloud self-gravity. Therefore, as in King (2003), both momentum and energy of the UFO are important, the former for driving the cold clouds away whereas the latter for driving lower density gas to high outward velocities. It is important to emphasize at this point that the 'hot shocked phase' may well contain cooler cloud inclusions that are denser and could thus cool down, in principle all the way to temperatures at which molecules form. This phase could be accelerated to high velocity and even form stars (Zubovas et al. 2013b).

(2) One of the key assumptions of our model is that gas is delivered to the SMBH by cold dense clouds. This naturally connects to the observational fact that accretion of hot virialized gas on SMBH is inefficient and proceeds at rates much lower than the expected Bondi rate (e.g. Baganoff et al. 2003; Di Matteo et al. 2003). This inefficiency is in contrast to the recent ideas about the 'chaotic AGN feeding' regime, in which clouds with randomly oriented angular

momentum are deposited into the central $\sim$ parsec of the host. King & Pringle (2006) argued that this helps to alleviate the problem of too large a spin of SMBHs that is not observed, Nayakshin & King (2007) and King & Pringle (2007) suggested that this would also solve the self-gravity 'catastrophe' of AGN discs (Goodman 2003; Nayakshin, Cuadra & Springel 2007). Hobbs et al. (2011) proposed that turbulence induced in the bulge by star formation may naturally produce such chaotic inflows (also see Barai et al. 2012; Gaspari et al. 2013, for related ideas).

We also suggested that density of clouds that eventually make it deep enough to feed the SMBH is limited by their self-gravity, since denser clouds participate in star formation instead. This makes a testable prediction: there can be no significant SMBH growth without star formation in the host, since if there are dense clouds then some of them are inevitably forming stars. This is consistent with the observations: star formation and bright AGN activity are well known to go hand in hand. For example, Chen et al. (2013) report a nearly linear correlation between star formation rates and SMBH accretion rates for a sample of star-forming galaxies with redshift $0.25 < z < 0.8$. This correlation is only statistical however, as we expect AGN luminosity to vary on short time-scales, possibly by multiple orders of magnitude (see more on that in Zubovas et al. 2013a), whereas star formation rate is not likely to vary on time-scales shorter than ~ 1 Myr.

(3) In spherically symmetric one-phase models, the $M-\sigma$ relation arises because the SMBH drives gas outward, limiting its own growth. In our model, this is only part of the answer; SMBH growth is limited by both the outward push and star formation triggered in the host by the UFO. In our model, AGN feedback does not terminate star formation in the host as is often assumed, it rather accelerates it when it can (while the cold ISM phase is abundant). The termination step does occur but only at late times when there is little gas in the bulge left. In this case, most of the ISM is in the hot phase, and it takes very little effort from the SMBH to remove it or stir it up to prevent cooling.

(4) The overall sign of AGN feedback is always negative, since in the absence of the outward forces caused by the feedback, all the gas that fell into the host could be eventually converted into stars. However, it is important in our picture that feedback of the AGN on to the galaxy's bulge can be both positive (triggered star formation) and negative (gas removal).

(5) It is also interesting to note that $M-\sigma$ relation is established inside quite a small part of the host bulge in the spherically symmetric model (King 2003), e.g. inside $R \lesssim R_{\rm ic} \sim 0.5$ kpc $M_8^{1/2}\sigma_{200}$. The size of the bulge is much larger, e.g. $R_{\rm b} = GM_{\rm bulge}/2\sigma^2 \sim 30$ kpc σ_{200}^2. Those large scales are readily cleared in the energy-driven regime in that model. This however implies that SMBH has a negligible effect on the host galaxy while $M_{\rm bh} < M_\sigma$, since the momentum-driven outflows stall in the region $R \lesssim R_{\rm ic}$ until the SMBH exceeds the M_σ mass. In our model, on the other hand, even black holes with mass $M_{\rm bh} \ll M_\sigma$ are important for their hosts because the outflow is in the energy-conserving mode and is able to percolate through the cold medium, therefore affecting the galaxy far and wide. Therefore, a key observational test of our model would be detection of an energy-driven massive outflow from an SMBH that is well below its M_σ mass. Such an outflow could not possibly exist in the homogeneous one-phase model for AGN feedback.

Cicone et al. (2012) report a massive outflow in the ultraluminous infrared galaxy (ULIRG) hosting galaxy Mrk 231, carrying as much as $\dot{M} \sim 700\,{\rm M_\odot\,yr^{-1}}$ of cold gas traced in CO and HCN molecular transitions. The outflow extends to ~ 1 kpc scale and shows

velocities of ~ 1500 km s^{-1}. Such energetics is consistent with the energy-driven flow that entrained molecular clouds. Interestingly, the authors find that the extent of the outflow anticorrelates with the critical densities of the line transition used to trace the outflow. They interpret this correlation as a signature that density of the clouds responsible for the lines observed decrease with radius, indicating that high-density clouds evaporate as they flow outwards. We note that this observation could be interpreted no less naturally in the context of our model. Since the pressure exerted by the UFO on to the clouds decreases with radius (see Zubovas et al. 2013a), clouds' density must indeed fall with increasing distance from the AGN. This conclusion does not require cloud destruction at all.

Finally, we emphasize that the analytical model developed here is an attempt to obtain a simple yet useful analytical insight into a very complicated problem. One must keep in mind that in reality there is a constant mass exchange between the phases, e.g. by cloud formation and destruction via thermal conduction evaporation, shocks and instabilities (e.g. McKee & Ostriker 2007; Faucher-Giguère, Quataert & Murray 2012). To give an example, a cold cloud moving on a radial trajectory out of the host could have started as a much lower density but hotter gas that was shocked and compressed by the UFO and then cooled down, all the while being accelerated outward. Thus, in this more detailed picture of the UFO–host ISM interaction one may expect some cold gas streaming outward in the bulge at velocities consistent with the energy-conserving flow, consistent with the observations. Furthermore, developments in the field should utilize numerical simulations to resolve the multiphase ISM shocked by the UFOs in more realistic detail.

4 CONCLUSIONS

Here, we attempted to extend the model of King (2003) for AGN feedback on the case when the ambient ISM in the host has a multiphase structure. In our two-phase approximation, the ISM consists of a cold dense phase, such as cold clouds and a hot tenuous phase that fills most of the volume. We proposed that the UFO overtakes the cold clouds, as supernova shock waves do. The clouds are affected by a strong but nearly isotropic compression due to the reverse shock in the UFO, and a smaller outward push. The interaction of the UFO with the hot ISM, on the other hand, is much closer to the spherically symmetric shock picture employed in previous work (e.g. King 2010; Zubovas et al. 2011). This phase is blown away from the bulge by the UFO easily but is constantly replenished by cloud ablation and destruction.

We showed that a combination of constraints from the outward push on the cold ISM and cloud destruction by star formation sets an $M-\sigma$ relation similar in form to that derived by King (2003). Main model predictions distinguishing it from previous work are (1) the importance of triggered star formation in the cold gas in limiting SMBH growth and (2) the ability of 'underweight' black holes to affect their hosts in the energy-conserving mode due to percolation of hot gas to large distances via low-density voids.

We believe that SMBH-host galaxy connections cannot be properly understood without taking into account the multi-phase structure of the ISM of the host.

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