Suppressing hot gas accretion to supermassive black holes by stellar winds

Shlomi Hillel* and Noam Soker

Department of Physics, Technion – Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

We argue that one of the basic assumptions of the Bondi accretion process, that the accreting object has zero pressure, might not hold in many galaxies because of the pressure exerted by stellar winds of a star orbiting the central supermassive black hole (SMBH). Hence, the Bondi accretion cannot be used in these cases, such as in the galaxy NGC 3115. The winds of these high-velocity stars are shocked to temperatures above the virial temperature of the galaxy, leading to the formation of a hot bubble of size $\sim 0.1–10$ pc near the centre. This hot bubble can substantially reduce the mass accretion rate by the SMBH. If the density of the hot bubble is lower than that of the interstellar medium, a density-inversion layer is formed. As the gas loses energy by X-ray radiation, eventually more mass of the cooling shocked stellar winds will be accreted to the SMBH. This accretion will likely be of cold clumps. After a period of millions of years of low active galactic nucleus (AGN) activity, therefore, stronger AGN activity will occur that will heat and expel gas, much as in cooling-flow clusters. Adding to other problems of the Bondi process, our results render the Bondi accretion irrelevant for AGN feedback in cooling flow in galaxies and small groups of galaxies and during galaxy formation.

Key words: accretion, accretion discs – ISM: bubbles – galaxies: clusters: general – galaxies: general – galaxies: individual: NGC 3115 – galaxies: ISM.

1 INTRODUCTION

It is widely accepted that feedback powered by active galactic nuclei (AGN) has a key role in galaxy formation and in cooling flows in galaxies and in clusters of galaxies. In galaxy formation, AGN feedback heats and expels gas from the galaxy (e.g. Bower, McCarthy & Benson 2008; Ostriker et al. 2010 and references therein), and by that it can determine the correlation between the central supermassive black hole (SMBH) mass and some properties of the galaxy (King 2003, 2005; Soker 2009; Soker & Meiron 2011). In cooling-flow clusters, jets launched by the SMBH heat the gas and maintain a small, but non-zero cooling flow (see the review by McNamara & Nulsen 2007, 2012; Fabian 2012); this is termed a moderate cooling flow.

There is a dispute on how the accretion on to the SMBH occurs, in particular in cooling flows. One camp argues for accretion to be of hot gas via the Bondi accretion process (e.g. Allen et al. 2006; Russell et al. 2010; Narayan & Fabian 2011), while the other side argues that the accretion is of dense and cold clumps in what is termed the cold feedback mechanism (Pizzolato & Soker 2005, 2010). The cold feedback mechanism has been strengthened recently by observations of cold gas and by more detailed studies (Revaz, Combes & Salomé 2008; Pope 2009; Wilman, Edge & Swinbank 2009; Cavagnolo et al. 2011; Nesvadba et al. 2011; Wilman et al. 2011; Farage, McGregor & Dopita 2012; Gaspari, Brighenti & Temi 2012a; Gaspari, Ruszkowski & Sharma 2012b; Kashi et al. 2012; McCourt et al. 2012; Sharma et al. 2012).

The Bondi accretion process, on the other hand, suffers from two problems. The first problem is that in cooling-flow clusters the Bondi accretion rate is too low to account for the AGN power (e.g. Cavagnolo et al. 2011; McNamara, Rohanizadegan & Nulsen 2011). The second is that there is no time for the feedback to work, i.e. to provide the feedback heating seen in cooling-flow clusters (Soker, Sternberg & Pizzolato 2009). This is because the time for cooling gas at distances of $\gtrsim$ few $\times$ kpc in the Bondi accretion process to be accreted and power jets that heat back the interstellar medium (ISM) is much longer than the cooling time of the gas. This is already true for gas cooling at a moderate distance of $\sim 1$ kpc from the centre. In other words, the gas at large distances has no time to communicate with the SMBH before it cools.

In this paper, we point out yet another problematic point with the Bondi accretion process. In a recent paper, Wong et al. (2011) resolved the region within the Bondi accretion radius of the S0 galaxy NGC 3115. If the density and temperature profile is interpreted as resulting from a Bondi accretion flow on to the $M_{\rm BH} = 2 \times 10^9 M_\odot$ central SMBH, the derived accretion rate is $\dot{M}_B = 2.2 \times 10^{-2} M_\odot$ yr$^{-1}$. They note that for a radiation power of $0.1 M_\odot c^2$, the expected accretion luminosity is six orders of magnitude above the observed upper limit. They attribute this to a process where either (i) most of the inflowing gas is blown away or (ii) the gas is continuously circulating in convective eddies.

*E-mail: shlomihi@tx.technion.ac.il

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Alternatively, they consider that the region they resolve is not yet incorporated into the Bondi accretion flow. We note that the idea of circulating eddies has some similarities to the density-inversion layer behaviour we discuss here.

In any case, some AGN activity does take place in NGC 3115 (Wrobel & Nyland 2012). Wrobel & Nyland (2012) detected a radio nucleus in NGC 3115 with a radio power of $L_{\text{radio}} = 3 \times 10^{35}$ erg s$^{-1}$. This indicates the presence of a weak AGN, that might substantially reduce the accretion rate (Wrobel & Nyland 2012). As we discuss later, the feeding of the SMBH might be from the stellar winds rather than from the ISM.

Several other processes were considered to reduce the accretion rate by an SMBH much below the Bondi accretion rate. Such processes include magnetic field reconnection (Igumenshchev & Narayan 2002), angular momentum (Proga & Begelman 2003a,b), magnetothermal instabilities (Sharma, Quataert & Stone 2008) and instabilities due to self-gravitation of the infalling gas (Levine, Gnedin & Hamilton 2010). Lack of spherical symmetry in realistic situations is an additional factor (Debuhr, Quataert & Ma 2011). Turbulent media can have a higher than the Bondi–Hoyle accretion rate, but due to vorticity, a lower accretion rate is also possible (Krumholz, McKee & Klein 2005, 2006). Hobbs et al. (2012) claim that the Bondi–Hoyle solution is only relevant for hot virialized gas with no angular momentum and negligible radiative cooling.

We take a different view on the suppression of the Bondi accretion. We argue that in many galaxies for a significant fraction of the time, the Bondi accretion flow might not be relevant because one cannot assume a zero pressure at the centre, either because of stellar winds or because of jets blown by the AGN.

### 2 THE PRESSURE OF STELLAR WINDS

The pressure exerted by stellar winds of high-velocity stars (i.e. moving much faster than the dispersion velocity in the galaxy) with an average mass-loss rate per star of $\dot{m}_\star$ can be calculated in two limits, which basically lead to the same result. First, we calculate the pressure by considering the total outward momentum flux at radius $r$. Because the orbital velocities of stars around the SMBH are much larger than the typical velocities of the stellar winds (as most of the mass-loss is during the asymptotic giant branch, AGB, phase), the relevant velocity in general is not that of the wind relative to the star, but rather the velocity of the star under the gravitational influence of the SMBH,

$$u_\star(r) \simeq \sqrt{\frac{GM_{\text{BH}}}{r}} \approx 2 \times 10^5 \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right)^{1/2} \left( \frac{r}{1 \text{ pc}} \right)^{-1/2} \text{ km s}^{-1}. \tag{1}$$

This holds as long as the SMBH gravity dominates that of the galaxy. In NGC 3115 that we study in more detail in Section 3, for example, the SMBH gravity dominates that of the galaxy to a distance of $\sim 30$ pc as the black hole mass is $M_{\text{BH}} = 2 \times 10^8 M_\odot$. Let stellar winds from high-velocity stars dominate the pressure inside a sphere of radius $R_\text{h}$. The pressure exerted by the wind on a surface of radius $R_\text{h}$ is approximately given by adding the ram pressures of winds from all stars inside the sphere of radius $R_\text{h}$,

$$P_{\text{ram}}(R_\text{h}) \simeq n_\star \eta \dot{m}_\star u_\star(R_\text{h}) \frac{4\pi R_\text{h}^2}{3} \frac{1}{4\pi R_\text{h}^3}, \tag{2}$$

where $n_\star$ is the stellar number density in the centre of the galaxy, and $\eta$ is the fraction of the mass lost by stars that is shocked and heats up. In all our expressions, the stellar mass-loss rate appears as $\dot{m}_\star$.

Some of the mass lost by stars will form dense clumps that will cool rapidly even if being shocked, or will not even be shocked. This is particularly true as most of the mass is being lost by AGB stars that have dense winds. The thermal pressure of the ISM in the centre will cause part of the winds’ gas to form dense clouds. Many of the cold clumps can be evaporated by heat conduction from the hot gas in the bubble. However, some clumps might flow inwards and feed the SMBH, and explain the AGN activity observed by Wrobel & Nyland (2012). The average mass-loss rate is calculated as follows. A solar-like star loses $\sim 0.5 M_\odot$ over $\sim 10^7$ yr. Considering an old population of stars, the mass-loss rate is lower even. More accurately, most of the mass-loss is due to AGB stars, which live for $\sim 10^7$ yr, and lose mass at an average rate of $\sim 10^{-7} M_\odot$ yr$^{-1}$ (Willson 2007). During the final stages of the AGB, the evolution is faster and the mass-loss rate is higher. If there is a young stellar population, the total mass-loss rate can be much higher. The ram pressure will not increase much beyond a few pc because the stellar density decreases.

Secondly, an alternative point of view would be to express the pressure as (roughly) the energy density of the shocked stellar wind. We also assume a constant pressure and density inside this sphere. This is justified because we are interested mainly in the outer part of the hot bubble, where density inversion might take place. Even a steep power-law profile, say of $\rho \sim r^{-2}$, will not change the density much from $0.5 R_\text{h}$ to $R_\text{h}$, which contains $0.875$ of the volume of the bubble. We can calculate the rate of energy input and multiply by the time it takes the hot gas to leave the inner region

$$\tau_{\text{esc}} = \frac{R_\text{h}}{\beta u_\star(R_\text{h})}, \tag{3}$$

where $\beta \lesssim 1$ takes into consideration that the hot gas at the centre escapes at a velocity lower than the escape velocity. The stellar wind pressure in this case can be written as

$$P_\text{es} = \frac{2}{3} \frac{E}{\beta u_\star(R_\text{h})}, \tag{4}$$

where the energy deposition rate is

$$E = \int_0^{R_\text{h}} \left( \frac{1}{2} n_\star \eta \dot{m}_\star u_\star(r)^2 \right) 4\pi r^2 \, dr = 2\pi GM_{\text{BH}} \eta \dot{m}_\star \int_0^{R_\text{h}} n_\star(r) r \, dr. \tag{5}$$

Scaling the different quantities and assuming a constant stellar density we find

$$P_\text{es} = 3 \times 10^{-5} \beta^{-1} \dot{m}_\star \left( \frac{M_{\text{BH}}}{10^8 M_\odot} \right)^{1/2} \left( \frac{R_\text{h}}{1 \text{ pc}} \right)^{1/2} \left( \frac{n_\star}{5 \times 10^5 \text{ pc}^{-3}} \right) \times \left( \frac{\dot{m}_\star}{10^{-10} M_\odot \text{ yr}^{-1}} \right) \text{ erg cm}^{-3}, \tag{6}$$

where the stellar density is scaled by the average stellar density within $\sim 3$ pc from the centre of NGC 3115 (Kormendy et al. 1996). Equations (4) and (6) are more accurate than equation (2) when the radiative cooling time of the colliding stellar winds is larger than the escape time $\tau_{\text{esc}}$, which is the case here due to the high-temperature low-density post-shock stellar winds. The radiative cooling time is $\tau_c = (5/2)nkT/(\dot{m}_\star n_p \Lambda) \simeq 10^7 - 10^8$ yr. This is much longer than the escape time given in equation (3), $\tau_{\text{esc}} \simeq 10^7 - 10^8$ yr. Here $n_e, n_p$ and $n$ are the electron, proton and total number density, respectively.
and \( \Lambda \) is the cooling function. Therefore, from now on we will refer to the hot gas region formed by the shocked stellar winds as the hot bubble, and to its radius as \( R_b \). For a constant stellar density within radius \( r \), we find \( \rho_{\text{rs}} = \frac{2}{3} \beta - 1 \rho_{\text{sw}} \). If the stellar density drops to zero at some radius \( r_s \) (a non-realistic ideal case), the pressure beyond \( r_s \) will drop like \((r/r_s)^{-2}\).

The average density of the hot shocked stellar wind is given by

\[
\rho_{\text{sw}} \approx \left( \frac{4\pi}{3} R_b^3 \right)^{-1} \eta m_i \frac{R_b}{\beta u_a(R_b)} \int_0^{R_b} 4\pi n_i(r)r^2 dr. \tag{7}
\]

The flow structure is schematically drawn in Fig. 1. Relevant to this flow structure are the simulations of Cuadra, Nayakshin & Martins (2008). They simulated the dynamics of stellar winds in the Galactic Centre and found the accretion rate to be highly variable, due in part to the stochastic nature of infalling cold clumps. Fryer et al. (2007) suggest that the inner \( \sim 5 \) pc region surrounding Sgr A* in our Galaxy can be approximated by a wind-blown hot bubble density structure.

\section{3 The Case of NGC 3115}

At the Bondi radius \( R_b \approx 210 \) pc of the galaxy NGC 3115, the ISM pressure is \( P(R_b) = 2 \times 10^{-14} \) erg cm\(^{-3}\), the electron number density is \( n_e(R_b) = 0.02 \) cm\(^{-3}\) and the temperature is \( T(R_b) = 3.5 \times 10^6 \) K (Wong et al. 2011). The Bondi radius is given by

\[
R_b \approx \frac{2GM_{\text{BH}}}{c^2} \approx 220 \left( \frac{M_{\text{BH}}}{2 \times 10^9 M_\odot} \right) \left( \frac{T}{3.5 \times 10^6 \text{K}} \right) \text{pc}, \tag{8}
\]

where \( c_s \) is the sound speed in the undisturbed gas. The temperature and electron density increase inwards, reaching values of \( T_{20} \approx 10^7 \) K and \( n_{e20} \approx 0.3 \) cm\(^{-3}\) at \( r = 20 \) pc (Wong et al. 2011; no values are given at smaller radii). We also note that in NGC 3115 the BH gravity dominates that of the galaxy to a distance of \( \sim 30 \) pc as the black hole mass is \( M_{\text{BH}} = 2 \times 10^8 M_\odot \).

The average density and pressure of the hot bubble according to equations (7) and (6) are drawn in Fig. 2 for an SMBH mass of \( M_{\text{BH}} = 2 \times 10^9 M_\odot \), and a stellar density given by

\[
n_s = \begin{cases} 5 \times 10^5 \text{pc}^{-3} & r \leq 3 \text{ pc} \\ \left(r/3 \text{ pc}\right)^{-3} & r > 3 \text{ pc}, \end{cases} \tag{9}
\]

and for \( \beta = 1 \) (equation 3) and \( \eta = 0.1 \) (equation 2). The density within \( r = 3 \) pc is from Kormendy et al. (1996), while that at \( r > 3 \) pc is our assumption. The particular form of the decline in stellar density at \( r > 3 \) pc has no significant consequences, and the particular power law was chosen for the sake of simplicity and definite calculations. The value of the mass-loss efficiency, which is the fraction of the mass lost by stars that ends up as hot gas in the hot bubble, is chosen as \( \eta = 0.1 \) to more or less match the pressure and density of the ISM at \( r = 20 \) pc. It is a parameter of the model that should be typically in the range of \( 0.1 \)–\( 1 \). The temperature that is calculated from the pressure is also drawn in Fig. 2. Beyond \( \sim 30 \) pc, the average temperature is only approximately two times as large as the virial temperature of the cluster, and our assumptions of a hot bubble become inadequate.

The following conclusions emerge from Fig. 2. (1) The pressure of the shocked stellar winds of the high-velocity circum-SMBH stars is larger than the ISM pressure near the centre, even for a mass-loss efficiency of only \( \eta \sim 0.1 \). This accounts, we argue, for the accretion rate of NGC 3115 being much lower than the Bondi accretion rate (Wong et al. 2011). (2) At the centre, \( r < 3 \) pc, the rate of mass-loss into the hot gas per unit volume is \( \dot{\chi} \equiv \eta n_s \dot{n}_{\text{sw}} \) \( = 5 \times 10^{-6} M_\odot \text{pc}^{-3} \text{yr}^{-1} \). Even if this value is 10 times lower, a hot bubble with pressure larger than the ISM pressure of NGC 3115 can still be formed. (3) For \( \dot{\chi} \lesssim 10^{-6} M_\odot \text{pc}^{-3} \text{yr}^{-1} \), the hot bubble’s density is lower than that of the ISM. This structure is Rayleigh–Taylor (RT) unstable. This structure is analysed below.

We note that the structure presented here is a temporary one. Eventually, the gas in the centre originated from stellar winds will radiatively cool and form cold clumps. Some will be accreted and amplify the AGN activity. Many other clumps will be evaporated by the hot bubble and by the new AGN activity. Accretion of clumps on to an SMBH in a turbulent medium was studied by Hobbs et al.
and we expect the RT instability to break the cells to smaller cells. We therefore take the size of the rising and falling gas elements to be $R_c \ll l_p$.

We take the density-inversion zone to be of the order of the pressure scale height (in stars it can be much smaller). For a central gravity source, the pressure scale height for a constant temperature is given by

$$l_p = R_b \left[ \frac{C_s}{u_s(R_b)} \right]^2,$$

where $C_s$ is the isothermal sound speed, and $u_s(R_b)$ is the stellar velocity given in equation (1) and evaluated at the radius of the hot bubble $R_b$. The shocked stellar wind will be heated to a temperature of $T \approx (3/16)mu_*^2/k$, where $m$ is the mean mass per particle in the gas. The sound speed is $[(5/3)kT/m]^{1/2} \approx 0.6u_*$. Thus, we can take $l_p \sim R_b$. Therefore, we assume first that the width of the density-inversion layer is $\Delta r_i \sim R_b$.

Consider then a spherical parcel of gas (a blob) of radius $R_c$ and density of $\rho_c$ moving with a terminal velocity $v_t$ through an external medium of density $\rho_s$. The buoyancy force on the blob is

$$F_b = (\rho_c - \rho_s) \frac{4}{3} \pi R_c^3 g.$$

where $g$ is the gravitational acceleration. The drag force on the bubble is

$$F_d \approx \frac{1}{2} C_D \pi R_c^2 \rho_s v_t^2,$$

where $C_D \approx 0.75$ (Kaiser 2003). Assuming $\rho_c \ll \rho_s$ and taking $g = u_*^2/R_b$, the terminal velocity of the bubble is

$$v_t \approx \left( \frac{8}{3C_D} \right)^{1/2} \left( \frac{R_c}{R_b} \right)^{1/2} u_* = \beta u_*,$$

where in the second equality we identify the terminal velocity as the velocity by which the hot gas escapes from the hot bubble outwards, with

$$\beta \approx 0.6 \left( \frac{R_c}{0.1R_b} \right)^{1/2}.$$

5 DISCUSSION AND SUMMARY

We studied the pressure exerted by the winds of circum-SMBH high-velocity stars on the surrounding ISM. We found that in some cases this pressure is significant and can substantially suppress the inflow of the ISM relative to what a simple Bondi accretion would give. Our result can explain the finding of Wong et al. (2011) that the Bondi accretion rate calculated by them from the ISM density and temperature is six orders of magnitude above
the observed upper limit on the accretion rate in the S0 galaxy NGC 3115. In Section 3 we quantitatively examined the situation in the galaxy NGC 3115. Shocked winds of circum-SMBH high-velocity stars form a bubble of hot gas whose pressure is significant, as evident from Fig. 2. The colliding winds heat up to very high temperatures, build significant pressure and are not expected to be accreted by the SMBH even though they lose angular momentum. Cooler clumps that fall inwards, from the ISM or from inhomogeneities within the hot bubble, will encounter the winds of fast-moving stars very close to the SMBH. This collision will heat such clumps, suppressing their accretion. Even if there is a small accretion rate, a very weak disc wind from the accretion disc might further lower the accretion rate. Infrequent episodes of high accretion rate are expected to take place (see below). The study of the interaction of AGN winds with the gas near the SMBH is a subject of a future study using numerical simulations.

There are some uncertainties in the model, such as the exact behaviour of the stellar mass-loss, trajectories of stars around the SMBH and the stochastic behaviour of the post-shock stellar winds. Some of these will be studied in future numerical simulations. However, the result that the stellar winds cannot be ignored is robust.

For some values of the parameters we found that a situation might arise where the hot bubble’s density is lower than the ISM density. In this case, RT instability takes place, and a density-inversion layer is formed (see the schematic description in Fig. 1). Although hot tenuous gas buoyants outwards and dense ISM gas moves inwards, the density-inversion layer itself continues to exist. The ISM gas is heated near the centre and accumulated into the hot bubble.

While the scenario suggested here may explain the low X-ray luminosity observed in the galaxy NGC 3115, its properties have not yet been observed or confirmed directly. The size of the hot bubble described is below the resolution limit of the observations and cannot yet be observed. Alternative explanations for a below Bondi accretion rate are mentioned in Section 1.

We note that in our scenario there can be no steady state over a very long time of $\sim 10^7-10^8$ yr. Over this time-scale, radiative cooling becomes important and more of the cooling gas will be accreted by the SMBH. This will lead to stronger AGN activity that will heat and expel gas, hence reducing back the accretion rate and AGN power. In addition, stellar formation must occur from time to time. Most likely, there are local starburst episodes when the accretion rate is much higher than the Bondi accretion rate. The high accretion rate is probably driven by cold clumps (filaments, streams). Indeed, the stellar wind pressure cannot prevent accretion of very dense clouds. Between these high-accretion episodes, the accretion rate is very small.

Our result is more general in showing that in many cases the Bondi accretion process does not work because one of its basic assumptions, that there is no central pressure, breaks down. This is one of several reasons why the Bondi accretion model may not apply in some cases (see Section 1).

Finally, we note that our model may be relevant for active galaxies where the hot bubble might be formed by the AGN jets or winds. For typical values of AGN jets and winds, the hot bubble density will be low, and a density-inversion layer will be formed. We expect this process to be of high significance in the process of AGN feedback acting in young galaxies. Barraging Bondi-like accretion, dense and cold clumps in the ISM can still flow inwards and feed the SMBH. Namely, AGN feedback mechanisms require the feeding to be done by cold clumps, i.e. a cold feedback mechanism.

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