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Radiative pressure feedback by a quasar in a galactic bulge

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ABSTRACT

We show that Eddington-limited black hole luminosities can be sufficient to deplete a galaxy bulge of gas through radiation pressure, when the ionization state of the gas and the presence of dust are properly taken into account. Once feedback starts to be effective it can consistently drive all the gas out of the whole galaxy. We estimate the amount by which the effect of radiation pressure on dusty gas boosts the mass involved in the Eddington limit, and discuss the expected column density at which the gas is ejected. An example is shown of the predicted observed nuclear spectrum of the system at the end of an early, obscured phase of growth when the remaining column density $N_{\rm H} \sim 10^{24}\ f\ {\rm cm}^{-2}$, where f is the gas fraction in the bulge.

Key words: radiative transfer – galaxies: nuclei – galaxies: ISM – quasars: general.

1 INTRODUCTION

Much observational work over the past decade has shown that the mass of the central black hole in a galaxy, $M_{\rm BH}$, scales with the mass and/or velocity dispersion, σ, of the bulge of that galaxy (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese et al. 2001). A recent correlation (Tremaine et al. 2002) shows that $M_{\rm BH} \propto \sigma^4$ holds over at least three decades in black hole mass. This result suggests that black hole and galaxy growth are entwined and introduces the exciting possibility that the growth of a central black hole determines the properties of its host galaxy.

Many models have been produced to explain the $M_{\rm BH}$–σ correlation. The ones relevant here involve a central active galaxy influencing the level of gas, and thus star formation, of the host galaxy. The black hole may for example grow in mass and power until it is capable of ejecting the interstellar medium from the galaxy, thus stopping star formation and determining the total stellar mass of the galaxy. Such models employ either an energy argument (Silk & Rees 1998; Haehnelt, Natarajan & Rees 1998; Wyithe & Loeb 2003) which leads to $M_{\rm BH} \propto \sigma^5$, or a momentum one using a quasar wind (Fabian 1999) or the quasar radiation directly (Fabian, Wilman & Crawford 2002; King 2003; Murray, Quataert & Thompson 2005) to obtain $M_{\rm BH} \propto \sigma^4$. More general heating models have been presented by Granato et al. (2005) and by Sazonov et al. (2005), while Begelman & Nath (2005) explored the role of momentum in self-regulating the gas density profile.

The binding energy of the likely interstellar medium of a galaxy is less than 1 per cent of the energy released by the growth of its massive central black hole. This energy must of course be supplied in order to eject the gas. Sufficient momentum is also essential, which makes the overall process energetically inefficient.

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Here we revisit the momentum approach using radiation pressure from a central quasar acting on the dense star-forming interstellar medium of a young galaxy. The obvious approach is to use the Eddington limit, but in its original form it applies to a point mass while here we wish to deal with a galaxy which is a distributed mass. If the standard Eddington limit cannot be exceeded and is applied to both quasar and galaxy, then there is no way that the quasar radiation can eject the surrounding galactic medium since the mass and thus the Eddington-limiting luminosity required rise with radius. One approach (King 2003) is to invoke super-Eddington radiation levels from the quasar. There is, however, little observational evidence for super-Eddington radiation (e.g. Woo & Urry 2002; Kollmeier et al. 2006) or firm theoretical basis for it (but see Begelman 2002). Here we introduce an *effective* Eddington limit which occurs when radiation acts on lowly ionized and dusty gas. The quasar can easily exceed this limit and so drive gas from the galaxy. Of particular interest here is the column density of the gas within the galactic bulge.

2 THE EDDINGTON LIMIT

We now derive an effective Eddington limit for the situation when the radiation from a central active galaxy or quasar interacts with dusty, partially ionized gas. The effective interaction cross-section, due to photoelectric absorption, dust extinction etc., can then be much larger than the Thomson cross-section used to derive the standard Eddington limit. A central quasar at the standard Eddington limit for its mass, relevant for highly ionized gas in its immediate vicinity, can be radiating at, or above, the *effective* Eddington limit for distant matter gravitationally bound by the higher mass of the black hole and the host galaxy.

The Eddington limit arises when the outgoing radiation pressure, due to electron scattering, from a source of luminosity L balances the gravitational attraction due to its mass M:

$$L_{\mathrm{Edd}} = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{T}}}. \quad (1)$$

It is assumed here that radiation pressure is acting on a gas of ionized hydrogen around the photon source. G, m_{p} and σ_{T} are the gravitational constant, proton mass and Thomson cross-section, respectively. If the cross-section for interaction between the radiation and matter σ_{i} is larger than for electron scattering, then the relevant limit which we denote the effective Eddington limit L'_{Edd} is proportionally changed. Furthermore, the Eddington limit is often derived by considering an isolated electron–proton pair exposed to the radiation force. Here we need the effects of radiation on shells of matter surrounding the source so we consider the effective limit for a column density of gas N. For a gas optically thin to Thomson scattering, $L'_{\mathrm{Edd}} \simeq L_{\mathrm{Edd}}\, \tau_{\mathrm{T}}/\min\,[\tau_{\mathrm{i}}, 1]$, where τ_{T} and τ_{i} are the optical depths for the corresponding cross-sections, $\tau \equiv \sigma N$.

This means that a luminosity which is sub-Eddington for completely ionized gas close to a central mass, M, can exceed the modified Eddington limit for partially ionized or neutral gas, for which $\sigma_{\mathrm{i}} > \sigma_{\mathrm{T}}$, that is denser or further away. Note that σ_{i} is an effective cross-section obtained by averaging over the incident spectrum, the column density of matter and the state of that matter (ionization state, dust content, chemical composition, etc.). It therefore depends on the spectral shape of the incident radiation. Here we refer to the integrated spectrum and thus to an average cross-section. The absorbed luminosity corresponds to $L_{\mathrm{a}} \simeq L\, \tau_{\mathrm{i}}$ in the optically thin regime and $L_{\mathrm{a}} \simeq L$ for optically thick gas. We assume that L_{a} is radiated isotropically by the absorber and thus the resultant rate of change of momentum per unit area, or radiation pressure, is $L_{\mathrm{a}}/4\pi r^2 c$.

The amplification factor A, due to the presence of gas not fully ionized and dust, can be defined as the ratio of the effective radiation pressure $L \min\,[\tau_{\mathrm{i}}, 1]/4\pi r^2\, c$ acting outward on a column N gas at radius r with respect to that for fully ionized gas. This corresponds to

$$A = \frac{L_{\mathrm{a}}}{L \tau_{\mathrm{T}}} = \frac{\min[\tau_{\mathrm{i}}, 1]}{\tau_{\mathrm{T}}}. \quad (2)$$

Alternatively, this can be re-expressed in terms of the mass required gravitationally to hold this column density back from expulsion, which in terms of A can be written as

$$M'_{\mathrm{Edd}} = A M_{\mathrm{BH}}. \quad (3)$$

The latter expression assumes that the central black hole, of mass M_{BH}, is radiating at its (Thomson scattering) Eddington limit, so $L = L_{\mathrm{Edd}}$.

3 THE EDDINGTON BOOST FACTOR

We have determined the boost factor, A, by finding the luminosity absorbed by column density N_{H}, after making assumptions about the ionization parameter of the gas and incident radiation spectrum. For this purpose we use the code CLOUDY 96.01 (Ferland 1993) with the active galactic nucleus (AGN) spectrum. This essentially assumes an ultraviolet blackbody plus an X-ray power-law spectrum appropriate for a supermassive, radiatively efficent, accreting black hole.

The boost factor is obtained from the directly absorbed radiation. We subtract from the input luminosity that which is transmitted (without any diffuse radiation which is assumed to be isotropic). Basically we are using the continuum radiation pressure and assuming that the absorbed radiation emerges as heat which, on emission, interacts either little or with no dynamical consequences on the galactic gas. Trapping of radiation is assumed to be negligible. The procedure has been stepped over a range of column density N_{H} and ionization parameter $\xi = L/nr^2$ with the results plotted as A in Fig. 1a. Different symbols represent the cases with no dust and gas with a Galactic mix of dust. We expect that this covers the conditions in growing galaxies. If there is vigorous star formation and a high metallicity in the gas surrounding growing massive black holes then the gas should be very dusty.

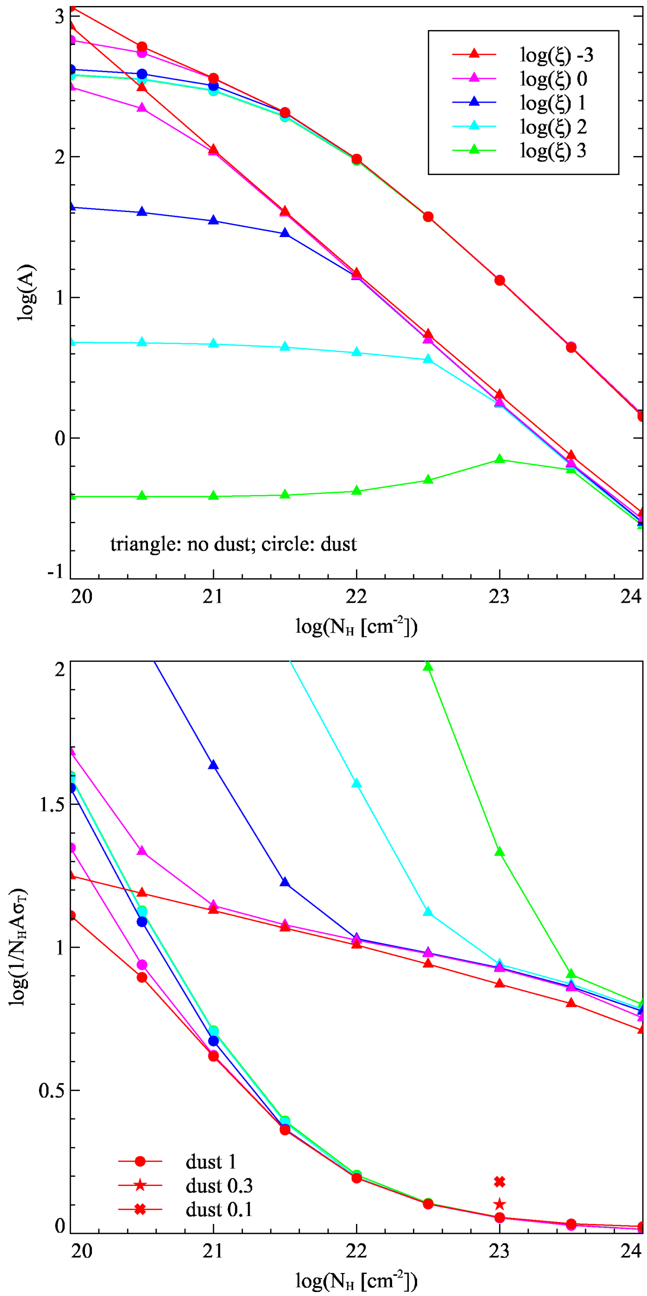

Figure 1. Top: boost factor A as a function of column density (expressed in terms of neutral hydrogen column N_{H}) and for various values of the ionization parameter $\log \xi$ from -3 to 3. Circles denote gas with a Galactic mix of dust, while triangles denote the case with no dust. (b) Bottom: factor $1/N_{\mathrm{H}}\; A\; \sigma_{\mathrm{T}} = L/L_{\mathrm{a}}$ shown as a function of column density. For dusty ionized gas, the factor is close to unity for $N_{\mathrm{H}} > 10^{23}$ cm^{-2} and less than 2 for $N_{\mathrm{H}} > 5 \times 10^{21}$ cm^{-2}. The effects of having the dust-to-gas ratio at 0.3 and 0.1 times the Galactic interstellar medium value are shown for a column density of 10^{23} cm^{-2}.

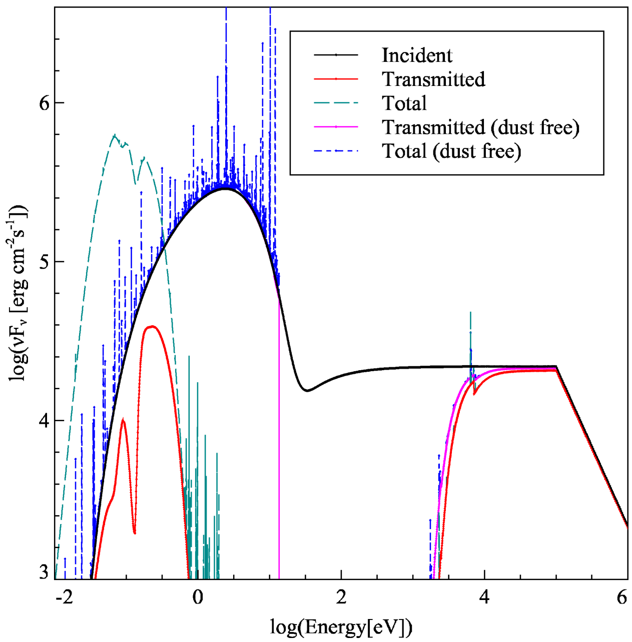

Figure 2. Input, transmitted and total emergent spectra for a dusty shell with column density $N_{\rm H} = 10^{23}\,{\rm cm}^{-2}$ and ionization parameter $\xi = 100$. The corresponding spectra for no dust are also shown. The normalization of the *y*-axis is arbitrary.

Overall the boosting factor is independent of $N_{\rm H}$ (see particularly the cases without dust), and just given by the ratio of the effective optical depth with respect to the Thomson one, until the gas becomes optically thick. For larger columns the radiation pressure does not increase further, while gravity acts on a more massive shell, leading to $A \propto N^{-1}$. The normalization of A in the optically thin regime and the column corresponding to an effective depth of unity clearly depend (inversely and directly, respectively) on the ionization state of the gas, parametrized by ξ.

As shown below, the effect of dust is to boost the effect of radiation pressure by one or more orders of magnitude, which – as discussed later – is key to ensure that gas can be depleted from a proto-galaxy for Eddington luminosities from the central black hole. The transmitted and total spectra for a column density $N_{\rm H} = 10^{23}\,{\rm cm}^{-2}$ and ionization parameter $\xi = 100$ are shown in Fig. 2 for both the dusty and dust-free cases. It is clear that much more radiation is absorbed in the dusty case with the radiation from the nucleus much reduced at energies above 0.3 eV or shorter than 3.6-μm wavelength. This means that the radiation pressure from much of the large ultraviolet/optical blackbody emission is harnessed, so causing the threefold or more increase in the boost factor A, when compared with the dust-free case. Since most of the radiation is absorbed in the dusty case ($L_{\rm a}$ is close to L), Fig. 1 follows straightforwardly from equation (2). The precise energy of the resulting infrared emission bump depends on the dust temperature and thus on the radial distribution of the dust.

The energy of the blackbody emission, assumed to originate from an accretion disc around the black hole, depends on the black hole mass, shifting to higher energies as the mass reduces. This means that the difference between the dusty and dust-free cases reduces for lower mass objects ($M_{\rm BH} < 10^8\,{\rm M}_\odot$). The blackbody peak is absorbed for all relevant masses for the dusty case, so we expect the resulting $M_{\rm BH}$–σ relation to be robust where the other assumptions hold.

4 EXPULSION OF GAS FROM A GALAXY

Let us consider now the specific case of a galactic bulge, and in particular follow the scenario discussed by Fabian (1999) and Fabian et al. (2002). It is assumed that the bulge is isothermal with mass-density profile $\rho \propto r^{-2}$. The total mass within radius r is given by

$$M = \frac{2\sigma^2 r}{G} \tag{4}$$

of which fraction f is assumed to be in gas, and this has been accreted on to the black hole, so $M_{\rm BH} = fM$. The column density exterior to r is then

$$N = \frac{f\sigma^2}{2\pi G m_{\rm p} r}. \tag{5}$$

It should be noted that in Section 2 we treated the gravitational force as acting on gas concentrated in a thin shell at distance r, while the bulge gas is distributed, and this leads to an extra factor $\ln(r_{\rm max}/r)$ where $r_{\rm max}$ corresponds to the outer boundary of the isothermal distribution (Fabian et al. 2002).

As previously mentioned, accretion on to the black hole within r leaves a column density given by equation (5) beyond. Our treatment of such a column being concentrated in a shell corresponds to the possible scenario where the very same radiation pressure would compress the gas into a shell propagating outward. Alternatively, one has to consider the extra logarithmic factor: although the value of $r_{\rm max}$ is not clearly determined a priori, there has to be a outer boundary of the (otherwise diverging) isothermal mass distribution $\propto r^{-2}$. Finally, we note that equation (5) also arises if the gas within r is assumed to be swept up into a shell rather than accreted into the black hole.

The question that we want to answer quantitatively here is whether radiative feedback from the central accreting black hole is sufficient to deplete gas on the galactic scale.

Gas is expelled from the bulge when the luminosity of the accreting black hole L exceeds the modified Eddington luminosity, namely $A > 1$. Or, more precisely, gas at radius r is pushed outward when $M'_{\rm Edd}$ for the column external to the gas exceeds the mass internal to r. Combining equations (2), (4) and (5) with $L = L_{\rm Edd}$, this corresponds to

$$\frac{L_{\rm a}}{4\pi c} = \frac{f\sigma^4}{\pi G}, \tag{6}$$

or from equations (3), (4) and (5),

$$M_{\rm BH} = \frac{f\sigma^4}{\pi G^2 m_{\rm p} A N}. \tag{7}$$

The computation presented in Section 3 shows (Fig. 1, bottom panel) that $AN\sigma_{\rm T}$ is close to unity over a wide range of column densities from 10^{22} to $10^{24}\,{\rm cm}^{-2}$. This means that we can replace AN by $\sigma_{\rm T}{}^{-1}$ in the above equation, so obtaining

$$M_{\rm BH} = \frac{f\sigma^4}{\pi G^2 m_{\rm p}}\sigma_{\rm T}. \tag{8}$$

This is the same expression, within a factor of 2, as that derived on simpler grounds by Fabian (1999), Fabian et al. (2002), King (2003) and Murray et al. (2005). What we have done here is to consider a more realistic gas composition and incident spectrum, and quantitatively to consider the effect of dust. The result is obtained principally because most of the relevant incident radiation, that in the ultraviolet to soft X-ray bands, is absorbed by column densities greater than $10^{22}\,{\rm cm}^{-2}$ of dusty gas which is not completely ionized.

Note that the resulting black hole mass (equation 8) depends on the Eddington fraction of the source as f_{Edd}^{-1}, so is larger for sources operating below the Eddington limit. Kollmeier et al. (2005) find in their sample of quasars at redshifts $z = 0.3$–2 that most are within a factor of 10 of the Eddington limit.

We have assumed that the outer gas is all in a shell at radius r, which slightly overestimates the force required. Radiation pressure will sweep matter into a dense shell, the column density of which will evolve as $N \propto r^{-1}$. Provided that it is still within the regime where AN is constant, then it will still be driven outward.

The ionization parameter of matter at radius r when it is about to be ejected is

$$\xi = \frac{L 2\pi G m_{\mathrm{p}}}{f \sigma^2}, \tag{9}$$

but at that point $L \approx L_{\mathrm{a}}$, so from (6)

$$\xi = 8\pi c m_{\mathrm{p}} \sigma^2 = 160 \sigma_2^2, \tag{10}$$

where we use $\sigma = 100\sigma_2\,\mathrm{km\,s^{-1}}$. This means that the line in Fig. 1 for $\xi = 100$ is the important one for the general case. We envisage that the gas is dusty and so the upper lines in the top panel of Fig. 1 are most relevant. The input and output spectrum for such a case are shown in Fig. 2.

5 DISCUSSION

In a very simple model, we envisage that the black hole grows by accreting the inner gas. Its mass $fM(r)$ then increases with time, its (standard Eddington-limited) luminosity L rises with mass and the column density N of the gas beyond r decreases until the condition given by equation (3) is met. The value of A at this point is $1/f$ and $N \approx f N_{\mathrm{T}}$. For gas fractions of 10 per cent the final column density is then $\sim 10^{23}\,\mathrm{cm^{-2}}$. The gas is then ejected from the host galaxy.

If the luminosity is sub-Eddington then $N \approx f f_{\mathrm{Edd}} N_{\mathrm{T}}$. The whole mechanism will fail if $f f_{\mathrm{Edd}}$ is much less than 0.01 at which point AN is no longer close to N_{T}.

The inner radius of the gas when expulsion occurs is (from equation 5)

$$r_{\exp} = \frac{\sigma^2}{2\pi G m_{\mathrm{p}}} \sigma_{\mathrm{T}}. \tag{11}$$

This is a factor of $(2f)^{-1}$ times the accretion radius ($r_{\mathrm{a}} = GM/\sigma^2$), so for a typical value of $f = 0.1$, $r_{\exp} \sim 5\, r_{\mathrm{a}}$. The region where most of the obscuration occurs is therefore compact.

Most of the black hole growth will have been by obscured accretion, as implied by the observed X-ray background (Fabian & Iwasawa 1999; see also Fabian 2004; Brandt & Brandt 2005; Worsley et al. 2004; Alexander et al. 2005; Civano, Comastri & Brusa 2005; Martinez-Sansigre et al. 2005) and mid-infrared studies with *Spitzer* (Treister et al. 2006). There is already a considerable population of known luminous AGN with column densities $N_{\mathrm{H}} \sim 10^{23}$–$5 \times 10^{23}\,\mathrm{cm^{-2}}$. In our model the main black hole growth phase occurs as the column density reduces to fN_{T}.

We do of course require that the black hole continues to be fuelled for the gas expulsion time which is several tens of millions of years. This could involve a torus and disc around the black hole, such as found in many models for AGN (see e.g. Antonucci 1993). Anisotropy of the radiation due to such structures will also cause the ejection not to be spherically symmetric. We consider that such issues are secondary to the basic model outlined above.

We have assumed that the gas is mostly cold and yet distributed throughout the bulge of the host galaxy in a manner similar to that of the stars. This requires that the gas is supported in some way and we assume that a pervasive hotter phase may be responsible. Cold clouds embedded in a hotter medium can drag the hotter medium with them when ejected. Why the distribution should be $\rho \propto r^{-2}$ is unexplained, although it must roughly occur if the gas clouds form into stars which appear to have this distribution.

The feedback process described here ultimately switches off growth of both black hole and host galaxy by radiation from the accreting black hole interacting with, and expelling, surrounding cold gas. Note that for the feedback mechanism to be effective implicitly allows for the cold gas component in the bulge to convert into stars. Different feedback processes are expected in massive galaxies, particularly those at the centres of groups and clusters where most surrounding gas is hot and ionized and so immune from the effects of radiation pressure on neutral and partially ionized gas. In such massive objects other processes are required for feedback (e.g. Churazov et al. 2005) and the slope and normalization of the $M_{\mathrm{BH}}-\sigma$ relation may change (Fabian et al. 2005).

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