The effect of radiation pressure on dusty absorbing gas around active galactic nuclei

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ABSTRACT

Many active galactic nuclei (AGN) are surrounded by gas which absorbs the radiation produced by accretion on to the central black hole and obscures the nucleus from direct view. The dust component of the gas greatly enhances the effect of radiation pressure above that for Thomson scattering so that an AGN which is sub-Eddington for ionized gas in the usual sense can appear super-Eddington for cold dusty gas. The radiation pressure enhancement factor depends on the AGN spectrum but ranges between unity and about 500, depending on the column density. It means that an AGN for which the absorption is long-lived should have a column density of \( N_H > 5 \times 10^{23} \lambda \) cm\(^{-2}\), where \( \lambda \) is its Eddington fraction \( L_{\text{bol}}/L_{\text{Edd}} \), provided that \( N_H > 5 \times 10^{21} \) cm\(^{-2}\). We have compared the distribution of several samples of AGN – local, Chandra Deep Field–South and Lockman Hole – with this expectation and find good agreement. We show that the limiting enhancement factor can explain the black hole mass–bulge mass relation and note that the effect of radiation pressure on dusty gas may be a key component in the feedback of momentum and energy from a central black hole to a galaxy.

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

1 INTRODUCTION

Active galactic nuclei (AGN) are powered by accretion on to a central massive black hole. The gas surrounding the nucleus, some of which provides the fuel for the accretion process, often obscures it from direct view. Indeed, the hard shape of the spectrum of the X-ray background argues that most accretion on to galactic nuclei is obscured (Fabian & Iwasawa 1999). This is confirmed by deep Chandra and XMM–Newton imaging of the Sky with many AGN found to lie behind a column density of \( 10^{22}–10^{23} \) cm\(^{-2}\) or more (Giacconi et al. 2002; Brandt & Hasinger 2005).

Much of the obscuring material must lie within the inner 100 pc, or its total mass would be prohibitive (see Maiolino & Risaliti 2007, for a review). It is therefore part of the inner bulge of the host galaxy. Stars can also form from this gas, giving a nuclear starburst. The gas is subject to the radiation pressure of the AGN, and can be ejected from the bulge if the nucleus becomes too bright. Such AGN feedback may thereby remove the gas which fuels the nucleus and from which new stars form, so terminating the growth of both the central black hole and its host bulge. Simple calculations of when this occurs (Fabian 1999; Fabian, Wilman & Crawford 2002; King 2003; Murray, Quataert & Thompson 2005; Fabian, Celotti & Erlund 2006) lead to the following relation between the mass of the black hole \( M_{\text{BH}} \) and the velocity dispersion of the bulge \( \sigma \):

\[
M_{\text{BH}} = \frac{f \sigma^4}{\pi G m_p} \sigma_T.
\]

Assuming a gas fraction \( f \sim 0.1 \), this gives an \( M_{\text{BH}}–\sigma \) relation in good agreement with observations (Kormendy & Richstone 1995; Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese et al. 2001).

The limit when radiation pressure ejects mass is an effective Eddington limit relying on absorption of radiation by dust, not on electron scattering. The radiation pressure is amplified or boosted by a factor \( A \) which is the ratio of the effective, frequency-weighted, absorption cross-section for dusty gas, \( \sigma_d \), to that for electrons alone:

\[
A = \frac{\sigma_d}{\sigma_T}.
\]

The dust absorption is greatest in the ultraviolet (UV) and the value of \( A \) depends on the spectrum of the AGN. The X-ray emission from the nucleus ensures that the gas and dust remain weakly ionized, and are effectively coupled by Coulomb forces so that pressure on the grains is shared with the surrounding gas.

Boost factors computed for a standard AGN spectrum, using the radiation code CLOUDY are shown in Fabian et al. (2006) and Fig. 1. They range from several hundred for low column densities and drop as the column density of gas increases until they approach unity when the gas becomes Compton thick, that is, \( N_H \sim 1/\sigma_T = 1.5 \times 10^{24} \) cm\(^{-2}\). Under the assumptions used, the main reduction of \( A \) with

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2 THE RELATION BETWEEN BOOST FACTOR AND EDDINGTON RATIO

We determine the boost factor $A$ as detailed in Fabian et al. (2006) using CLOUDY and AGN spectral energy distributions (SEDs) obtained by Vasudevan & Fabian (2007). $A$ is obtained from absorption only (the input spectrum minus the transmitted one) and assumes that the gas is optically thin to the infrared radiation thereby produced. Trapping of radiation is assumed to be negligible and the ionization parameter $\xi = L/nr^2$ is arranged to be about 10 (thereby fixing the gas density for a given incident AGN flux). Vasudevan & Fabian (2007) find that the UV–X-ray SEDs of AGN depend on Eddington ratio, with much more ionizing radiation – and therefore higher boost factors – occurring at higher $\lambda$. We adopt mean SEDs for high ($>0.1$) and low ($<0.1$) $\lambda$ when computing $A$ as a function of absorption column density. $N_H$ is plotted against $\lambda = A^{-1}$ in Fig. 2.

The drift velocity of the grains relative to the gas is computed by
\[ \frac{\rho_\text{grain}}{\rho_\text{gas}} = \frac{\xi}{\xi_\text{cr}} \]

where $\xi_\text{cr}$ is the critical ionization parameter for the gas to be ionized. The gas is assumed to be optically thin to the radiation from the AGN and the gas-dust interaction is assumed to be negligible.

Long-lived absorbing clouds can survive against radiation pressure in the shaded region of the figure. Clouds to the right-hand side of the dividing line, in the unshaded part, see the nucleus as above the Eddington luminosity and are thus ejected. Objects found in this region should be experiencing outflows and absorption may be transient or variable. The Compton-thick objects never see the source as exceeding the Eddington luminosity and so can be long-lived at all Eddington ratios less than unity. Gas clouds in this regime are more likely to change because of star formation.

Absorbed objects in the unshaded part at higher Eddington ratio should exhibit outflows, or the absorbing gas be far away from the nucleus where the retaining gravitational mass is much larger. They could for instance be associated with dust lanes, as envisaged by Matt (2000). Such absorption cannot be too large or the gas mass required would be prohibitive. We show, for example, a limit at $N_H = 5 \times 10^{21}$ cm$^{-2}$ in Fig. 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{The radiation pressure boost factor $A$ for dusty gas shown as a function of column density $N_H$. The continuum spectrum is assumed to be that of high and low Eddington ratio objects (from Vasudevan & Fabian 2007) for the upper and lower lines, respectively.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Fig. 1 replotted in terms of column density versus $1/A$. Long-lived absorption from clouds near the centre of the galaxy should occur in the shaded region. Absorption from clouds and dust lanes can occur at higher values of $A$, progressively farther out. High column densities there would require prohibitive gas masses so we restrict such a region to $N_H < 5 \times 10^{21}$ cm$^{-2}$, marked by a horizontal line.}
\end{figure}
Black hole masses are estimated from velocity dispersions and assume errors of 10 per cent on the $M_{\text{stellar}}/M_{\text{BH}}$ value of $10^{21}$ cm$^{-2}$. We used the same as for the CDFS sample. There were 13 objects for which mass estimates could be obtained. The results are shown in Fig. 4 (top panel); objects with negligible column density are marked nominally as having an upper limiting $N_{\text{H}}$ of $10^{17}$ cm$^{-2}$ (downward arrows). The range of Eddington ratios that we find for most objects lie within the shaded region. Note that since $N_{\text{H}} > 5 \times 10^{21}$ cm$^{-2}$, provided that $N_{\text{H}} > 5 \times 10^{21}$ cm$^{-2}$.

3 COMPARISON WITH DATA

The simple model described above predicts that most highly obscured AGN will be observed to have an intrinsic column density placing them in the shaded region of Fig. 2.

In order to test our model, we have examined the absorption and black hole mass of several samples. The first is a composite low-redshift sample consisting of the Markwardt et al. (2005) sample of AGN detected by the Burst Alert Telescope (BAT) on the Swift satellite, and the Dadina (2007) sample of Seyfert nuclei observed by the BeppoSAX satellite. The former is an all-sky, hard-X-ray-flux-limited sample in the energy range 14–195 keV where detection should be independent of column density, provided the source is not too Compton thick. The latter study presents an atlas of X-ray radiation pressure and absorption in AGN.

Our prediction is therefore that absorbed objects should lie above the approximate dividing line given by $N_{\text{H}} > 5 \times 10^{21}$ cm$^{-2}$, provided that $N_{\text{H}} > 5 \times 10^{21}$ cm$^{-2}$.

In this figure, we see one object with a large column density and high Eddington ratio in the unshaded region. This is NGC 2873, and the absorption is part of an outflowing warm absorber (Kaspi et al., 2001). The three objects with $22 > \log N_{\text{H}} > 21$ (just below the horizontal line) are, in order of increasing $\lambda$: IC 4329A, which has an outflow and is seen almost edge-on, so absorption may be from a distant dust lane (Markowitz, Reeves & Braito 2006); NGC 3516, which has variable absorption and an outflow (Markowitz et al. 2007); and 3C 120, which has a soft excess in XMM spectra (Ballantyne, Fabian & Iwasawa 2004), so may have $N_{\text{H}}$ overestimated in the value tabulated by Markwardt et al. (2005), used in Fig. 3.

We then used deeper samples. First, we use the Chandra Deep Field-South (CDFS) results of Tozzi et al. (2006). These authors provide values for the column density $N_{\text{H}}$ for each AGN together with intrinsic X-ray luminosities. We calculate black hole mass estimates using $K$-band magnitudes from Szkolny et al. (2004) and the $M_{\text{BH}}$-$L_{\text{K}}$ relation of Marconi & Hunt (2003). We impose a redshift cut, requiring our objects to lie between redshifts $0.5 < z < 1.0$. We attempt to account for some evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation between that epoch and our own by incrementing the $K$-band magnitudes by unity before using the relation (i.e. accounting for fainter bulge luminosities for the same central black hole mass in the past). This is broadly consistent with the evolution expected from van der Wel et al. (2006), assuming negligible evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation. We then used deeper samples. First, we use the Chandra Deep Field-South (CDFS) results of Tozzi et al. (2006). These authors provide values for the column density $N_{\text{H}}$ for each AGN together with intrinsic X-ray luminosities. We calculate black hole mass estimates using $K$-band magnitudes from Szkolny et al. (2004) and the $M_{\text{BH}}$-$L_{\text{K}}$ relation of Marconi & Hunt (2003). We impose a redshift cut, requiring our objects to lie between redshifts $0.5 < z < 1.0$. We attempt to account for some evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation between that epoch and our own by incrementing the $K$-band magnitudes by unity before using the relation (i.e. accounting for fainter bulge luminosities for the same central black hole mass in the past). This is broadly consistent with the evolution expected from van der Wel et al. (2006), assuming negligible evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation. We then used deeper samples. First, we use the Chandra Deep Field-South (CDFS) results of Tozzi et al. (2006). These authors provide values for the column density $N_{\text{H}}$ for each AGN together with intrinsic X-ray luminosities. We calculate black hole mass estimates using $K$-band magnitudes from Szkolny et al. (2004) and the $M_{\text{BH}}$-$L_{\text{K}}$ relation of Marconi & Hunt (2003). We impose a redshift cut, requiring our objects to lie between redshifts $0.5 < z < 1.0$. We attempt to account for some evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation between that epoch and our own by incrementing the $K$-band magnitudes by unity before using the relation (i.e. accounting for fainter bulge luminosities for the same central black hole mass in the past). This is broadly consistent with the evolution expected from van der Wel et al. (2006), assuming negligible evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation. We then used deeper samples. First, we use the Chandra Deep Field-South (CDFS) results of Tozzi et al. (2006). These authors provide values for the column density $N_{\text{H}}$ for each AGN together with intrinsic X-ray luminosities. We calculate black hole mass estimates using $K$-band magnitudes from Szkolny et al. (2004) and the $M_{\text{BH}}$-$L_{\text{K}}$ relation of Marconi & Hunt (2003). We impose a redshift cut, requiring our objects to lie between redshifts $0.5 < z < 1.0$. We attempt to account for some evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation between that epoch and our own by incrementing the $K$-band magnitudes by unity before using the relation (i.e. accounting for fainter bulge luminosities for the same central black hole mass in the past). This is broadly consistent with the evolution expected from van der Wel et al. (2006), assuming negligible evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation. We then used deeper samples. First, we use the Chandra Deep Field-South (CDFS) results of Tozzi et al. (2006). These authors provide values for the column density $N_{\text{H}}$ for each AGN together with intrinsic X-ray luminosities. We calculate black hole mass estimates using $K$-band magnitudes from Szkolny et al. (2004) and the $M_{\text{BH}}$-$L_{\text{K}}$ relation of Marconi & Hunt (2003). We impose a redshift cut, requiring our objects to lie between redshifts $0.5 < z < 1.0$. We attempt to account for some evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation between that epoch and our own by incrementing the $K$-band magnitudes by unity before using the relation (i.e. accounting for fainter bulge luminosities for the same central black hole mass in the past). This is broadly consistent with the evolution expected from van der Wel et al. (2006), assuming negligible evolution in the $M_{\text{BH}}$-$L_{\text{K}}$ relation.
the long-lived gas at column densities above $10^{22} \text{ cm}^{-2}$ is shielded by the inner gas and so need not be clumped.

After blowing away the gas, AGN may decline in luminosity, so creating unabsorbed sources at low Eddington ratios. There is also some uncertainty in the boundary between the various regions of the diagrams due to factors such as source variability and clumpiness in the absorption. The fact that most sources avoid the region of our diagrams above $N_H \sim 5 \times 10^{21} \text{ cm}^{-2}$ and to the right-hand side of the radiation pressure line demonstrates that variability is not very important.

Lower levels of absorption below $10^{22} \text{ cm}^{-2}$ can be long-lived at large radii in a galaxy, since the relevant gravitating mass there is due to the black hole and the bulge. The radiation limit in our figures shifts to the right-hand side by a factor of $M_{\text{bulge}}/M_{\text{BH}}$ with all gas above the line bound to the bulge. The maximum boost $A$ that can be obtained from radiation pressure on dusty gas is $\sigma_d/\sigma_T \sim 500$ which means that the black hole is above the effective Eddington limit for the whole bulge if $M_{\text{BH}}/M_{\text{bulge}} > 1/500$.

Consequently, we envisage a scenario where a black hole smoothed in gas could grow in a bulge in stages. It pushes the gas out to a distance in the bulge where the mass within that radius is 500 times the black hole mass. (The boost factor increases as the column density decreases, so once gas starts to move outwards it continues to do so, see Fig. 1 and Fabian et al. 2006.) After the accretion disc empties, the AGN switches off. If the bulge mass within the radius to which the gas was pushed exceeds 500 times the mass of the black hole, then the gas falls back in and the cycle repeats. Through accretion, the black hole mass and thus luminosity increases each cycle until it is unable to retain the gas and it is pushed right out of the bulge. At this point

$$\frac{M_{\text{BH}}}{M_{\text{bulge}}} \sim \frac{\sigma_T}{\sigma_d} \sim \frac{1}{500}$$

similar to the value found by Marconi & Hunt (2003) from correlating the observed properties of galaxies.

Star formation from the gas in the galaxy during these cycles presumably leads to the bulge mass–velocity dispersion (Faberg–Jackson) relation required such that equation (1), which acts locally, and equation (2), which acts globally, agree.

For much of the ‘cycling scenario’ envisaged above, the only acceptable range for bright unabsorbed objects would be at high Eddington ratios. From a large sample of AGN detected in their AGN and Galaxy Evolution Survey (AGES), Kollmeier et al. (2006) find $\lambda \sim 0.2$. An important result from their survey is that they should have been sensitive to unabsorbed AGN with lower Eddington ratios, but found none. This could in part be a selection effect due to absorption since the $\text{Chandra}$ X-ray observations used are short, about 5 ks, which means that they are most sensitive to bright unabsorbed objects. The discussion of emission line strength for high and low Eddington ratio AGN from Vasudevan & Fabian (2007) could also be of particular relevance here, again implying that higher Eddington ratio AGN would be systematically favoured. The detected objects are in the unshaded part of our diagram, so have high $\lambda$.

5 SUMMARY

Absorbed AGN are most commonly found at low Eddington ratios such that they are sub-Eddington for dusty gas. This agrees with the hypothesis that radiation pressure acting on dust is important in removing gas from galaxy bulges. In turn, this leads to $M_{\text{BH}}-\sigma$ and $M_{\text{BH}}-M_{\text{bulge}}$ relations similar to those observed.

Figure 4. The $N_H-\lambda = L_{\text{H}\alpha}/L_{\text{Edd}}$ plane with objects from the CDFS (top panel) using data from Tozzi et al. (2006) and Szokoly et al. (2004), and the Lockman Hole (bottom panel) using data from Mainieri et al. (2002) and Mateos et al. (2005). There is one point missing from each plot with $\lambda < 10^{-4}$.
Studies seeking to examine the evolution of absorbed AGN will need to include the dependence on Eddington ratio.

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