Black Hole Winds

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ABSTRACT

We show that black holes accreting at or above the Eddington rate probably produce winds which are optically thick in the continuum, whether in quasars or X-ray binaries. The photospheric radius and outflow speed are proportional to $\dot{M}_{\text{out}}^2$ and $\dot{M}_{\text{out}}^{-1}$ respectively, where $\dot{M}_{\text{out}}$ is the mass outflow rate. The outflow momentum rate is always of order $L_{\text{Edd}}/c$. Blackbody emission from these winds may provide the big blue bump in some quasars and AGN, as well as ultrasoft X-ray components in ULXs.

Key words: black hole physics – accretion – X-rays: galaxies – X-rays: binaries – quasars: general

1 INTRODUCTION

Recent XMM–Newton observations of bright quasars (Pounds et al., 2003) have revealed strong evidence for intense outflows at mass rates comparable to Eddington. Such outflows closely resemble those recently inferred in a set of ultraluminous X-ray sources (ULXs) with extremely soft spectral components (Mukai et al., 2003; Fabbiano et al., 2003). In the quasar PG1211+143 Pounds et al. (2003) find blueshifted X-ray absorption lines which show that the outflow has high velocity ($v \sim 0.1c$) The X-ray absorption columns in the quasar outflows are very large ($\sim 10^{24}$ cm$^{-2}$) suggesting that they may be Compton thick at small radii. Pounds et al. (2003) were able to use this information and the ionization state of the absorbing material to infer a mass outflow rate $\dot{M}_{\text{out}} \sim 1.6M_\odot$ yr$^{-1}$. This is close to the Eddington accretion rate $\dot{M}_{\text{Edd}}$ for this object.

Pounds et al. further showed that mass conservation strongly suggests that any outflow with $\dot{M}_{\text{out}} \sim \dot{M}_{\text{Edd}}$ is likely to be optically thick to electron scattering, with a photospheric radius $R_{\text{ph}}$ of order a few 10s of Schwarzschild radii $R_s = 2GM/c^2$, where $M$ is the black hole mass. The generic nature of the outflow characteristics at supercritical accretion rates (see e.g. eq. [3] below) strongly suggests that these outflows may be a widespread phenomenon, not only in currently observed systems such as quasars and ULXs, but also in the growth of supermassive black holes in the centres of galaxies in the past.

For the QSO PG1211+143 Pounds et al. (2003) found a photospheric radius $R_{\text{ph}} \sim 150R_s$ from their estimate of $\dot{M}_{\text{out}}/\dot{M}_{\text{Edd}}$. Although unremarked in that paper, the outflow velocity independently found from the X-ray absorption lines is very close to the escape velocity from this radius. Further, the outflow momentum rate $\dot{M}_{\text{out}}v$ is of precisely the same order as the radiation momentum rate $L_{\text{Edd}}/c$.

We show here that these features are just as expected in an optically thick wind driven by continuum radiation pressure. We use this to give simple scalings for the outflow velocity and photospheric radius $v, R_{\text{ph}}$ in terms of $\dot{M}_{\text{out}}/\dot{M}_{\text{Edd}}$.

2 OUTFLOWS FROM EDDINGTON–LIMITED ACCRETORS

We outline here a simple theory of outflows from black holes accreting at rates comparable with the Eddington value

$$\dot{M}_{\text{Edd}} = \frac{4\pi GM}{\eta c}.$$  

Here $\eta c^2$ is the accretion yield from unit mass, and $\kappa$ is the electron scattering opacity. We assume that the outflow is radial, in a double cone occupying solid angle $4\pi$, and has constant speed $v$ for sufficiently large radial distance $r$. We will justify the second assumption later in this Section. Mass conservation implies an outflow density

$$\rho = \frac{\dot{M}_{\text{out}}}{4\pi rv^2}.$$  

The nature of the outflow depends on $b$. If $b \sim 1$ we can neglect scattering of photons from the sides of the outflow, while for $b \ll 1$ this process is dominant. For completeness we first briefly revisit the case $b \sim 1$ (cf Pounds et al. 2003)

The electron scattering optical depth through the outflow, viewed from infinity down to radius $R$, is

$$\tau = \int_R^{\infty} \kappa \rho dr = \frac{\kappa \dot{M}_{\text{out}}}{4\pi rv^2 R}.$$  

From (1) we get
\[ \tau = \frac{1}{2\eta b} \frac{R_\text{ph}}{v} \frac{M_{\text{out}}}{M_{\text{Edd}}} \]  

(4)

Defining the photospheric radius \( R_{\text{ph}} \) as the point \( \tau = 1 \) gives

\[ \frac{R_{\text{ph}}}{R_\text{esc}} = \frac{1}{2\eta b} \frac{c \ M_{\text{out}}}{v} \simeq \frac{5}{6} \frac{c \ M_{\text{out}}}{b \ \eta \ M_{\text{Edd}}} \]  

(5)

where we have taken \( \eta \simeq 0.1 \) at the last step. Since \( b \leq 1, v/c < 1 \) we see that \( R_{\text{ph}} > R_\text{esc} \) for any outflow rate \( M_{\text{out}} \) of order \( M_{\text{Edd}} \), that is, such outflows are Compton thick.

If instead \( b << 1, \) photons typically escape from the side of the outflow rather than making their way radially outwards through all of it. Almost all of the photons escape in this way within radial distance \( r = R_\perp \) within which the effective photosphere is spherical, and there is no more acceleration. This justifies our assumption that \( v/c \) is constant for large \( r \), and it is self-consistent to use the assumption to integrate inwards to \( R_{\text{ph}}, \) or \( R_\perp \).

To ensure that the matter reaches the escape speed we require the radii \( R_{\text{ph}}, R_\perp \) to lie close to the escape radius \( R_{\text{esc}}, \) i.e.

\[ R_{\text{ph}}, R_\perp \simeq R_{\text{esc}} = \sqrt{\frac{c^2}{b^2}} R_\text{esc} \]  

(8)

From this equation and (4) we find

\[ \frac{v}{c} \simeq \frac{2 f L_{\text{Edd}}}{M_{\text{out}}} \quad \Rightarrow \quad \frac{R_{\text{ph}, \perp}}{R_\text{esc}} \simeq \left( \frac{M_{\text{out}}}{2 f L_{\text{Edd}}} \right)^2 \]  

(9)

where \( f = b, b^{3/2} \) in the two cases \( b \leq 1, b << 1 \). We can write these formulae more compactly as

\[ \frac{v}{c} \simeq \frac{2 f L_{\text{Edd}}}{M_{\text{out}} c^2} \]  

(10)

\[ \frac{R_{\text{ph}, \perp}}{R_\text{esc}} \simeq \left( \frac{M_{\text{out}} c^2}{2 f L_{\text{Edd}}} \right)^2 \]  

(11)

We note that \( f \sim 1 \) except for very narrowly collimated outflows \( b \leq 10^{-2} \).

An immediate consequence of (11) is

\[ \dot{M}_{\text{out}} v = \frac{2 f L_{\text{Edd}}}{c}, \]  

(12)

i.e. the momentum flux in the wind is always of the same order as that in the Eddington–limited radiation field, as expected for an Compton thick wind driven by radiation pressure. The energy flux (mechanical luminosity) of the wind is lower than that of the radiation field by a factor of order \( v/c \):

\[ \dot{M}_{\text{out}} \frac{v^2}{2} = \frac{v^2}{c} f L_{\text{Edd}} = \frac{2(f L_{\text{Edd}})^2}{M_{\text{out}} c^2}. \]  

(13)

### 3 THE BLACKBODY COMPONENT

Since the outflow is Compton thick for \( \dot{M}_{\text{out}} \sim \dot{M}_{\text{Edd}}, \) much of the accretion luminosity generated deep in the potential well near \( R_\text{esc} \) must emerge as blackbody-like emission from it. If \( b \sim 1 \) the quasi-spherical radiation area is

\[ A_{\text{phot}} = 4\pi b R_{\text{ph}}^2 \]  

(14)

If instead \( b \ll 1, \) the accretion luminosity emerges from the curved sides of the outflow cones, with radiating area

\[ A_\perp = 2\pi R_{\text{ph}} b^{3/2} \]  

(15)

We can combine these two cases as

\[ A_{\text{phot}, \perp} = 4\pi g \left( \frac{M_{\text{out}} c^2}{2 f L_{\text{Edd}}} \right)^2 R_\text{esc}^2 \]  

(16)

with \( g(b) = 1/b, 1/2b^{3/2} \) in the two cases. Again \( g \sim 1 \) unless \( b \leq 10^{-2} \), so the areas are similar in the two cases. However we note that the radiation patterns differ. In particular if \( b \) is small radiation is emitted over a wider solid angle than the matter. Numerically we have

\[ A_{\text{phot}, \perp} \approx 2 \times 10^{20} \frac{g M_1 M_8}{c^2} \text{ cm}^2, \]  

(17)

where \( M_1 = M_{\text{out}}/(1M_\odot\text{ yr}^{-1}), M_8 = M/10^8 M_\odot. \) The effective blackbody temperature is

\[ T_{\text{eff}} = 1 \times 10^8 g^{-1/4} M_1^{-1} M_8^{1/4} \text{ K}. \]  

(18)

Clearly such a component is a promising candidate for the soft excess observed in many AGN and ULXs.

### 4 DISCUSSION

We have investigated supercritical accretion \( (\dot{M} \geq \dot{M}_{\text{Edd}}) \) on to black holes. We assume that the excess matter is ejected, and have shown that the resulting outflow is Compton thick. The only alternative to this is to assume that the hole is able to accrete most of the mass at low radiative efficiency. However recent numerical simulations suggest (e.g. Stone & Pringle, 2001) that in this case most of the mass is ejected by the black hole rather than accreted.

We therefore expect that any black hole accreting at a rate \( \dot{M} \geq \dot{M}_{\text{Edd}} \) will show a strong Compton thick outflow, with effective photosphere of size a few 10s of \( R_\text{esc} \), scaling as \( M_{\text{out}}^{-1} \). The outflow velocity is of order the escape velocity from this photosphere, and scales as \( M_{\text{out}}^{-1} \). Observations of the QSO PG1211+143 strongly support this picture.

In this picture much of the accretion energy must be emitted from the photosphere with typical temperature given by (18). Mukai et al. (2003) and Fabbiano et al. (2003) use this to explain the very soft X–ray spectral components
found in some ULXs, although they were forced to assume an outflow velocity rather than estimating it self-consistently as here. This is in line with the suggestion (King et al., 2001; King, 2002) that ULXs are X-ray binaries where the current accretion rate $M \gtrsim M_{\text{Edd}}$. The particular ULX discussed by Fabbiano et al. (2003) has a blackbody temperature of order $10^6$ K, and eqn (18) shows that a $10M_\odot$ black hole would need an outflow (and thus mass transfer) rate of order $10M_{\text{Edd}} \sim 10^{-6}M_\odot$ yr$^{-1}$. This is not extreme for thermal timescale mass transfer in a massive X-ray binary ('SS433-like') or for a bright transient ('GRS1915+105-like'), the two situations envisaged for ULX behaviour by King et al. (2001) and King (2002). A similar value appears to hold for the ULX discussed by Mukai, where it is noticeable that the blackbody luminosity remains constant while the temperature changes by factors $\sim 2$.

An important question raised by our work is whether the outflow velocities discussed here can be identified with those of the jets seen in both classes of ULX. If so, the observed jet velocities would give direct information about $M_{\text{out}}/M_{\text{Edd}}$ and thus the accretion rate through eq (11). Thus the $v = 0.27c$ jets seen in SS433 would imply a mass transfer rate $\sim 5M_{\text{Edd}}$. This idea needs caution, as the jet may simply represent the fastest part of the outflow, rather than carrying most of the outflowing mass. In particular the jets are known to be inhomogeneous blobs rather than continuous outflow. Moreover jets are seen in systems where the luminosity is below or not significantly higher than $L_{\text{Edd}}$. Interestingly, it is clear that the radiation pattern in the microquasar GRS1915+104 (isotropic luminosity $\simeq 4L_{\text{Edd}}$, cf King, 2002) is indeed wider than the matter outflow, i.e. $b(\text{radiation}) > b(\text{outflow})$. This would agree with the suggested radiation pattern for the case $b(\text{outflow}) \ll 1$ discussed above.

The very general nature of the arguments presented here suggests that outflows may be the seat of ultrasoft components in ULXs, and of the big blue bump in AGN and QSOs accreting at close to the Eddington limit. It will be important to study how they interact with their surroundings.

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