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Black hole winds

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ABSTRACT

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

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

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 the Eddington rate. 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 PG 1211+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 $\dot{M}_{\rm out} \sim 1.6$ M$_\odot$ yr^{-1}. This is close to the Eddington accretion rate $\dot{M}_{\rm Edd}$ for this object.

Pounds et al. further showed that mass conservation strongly suggests that any outflow with $\dot{M}_{\rm out} \sim \dot{M}_{\rm Edd}$ is likely to be optically thick to electron scattering, with a photospheric radius $R_{\rm ph}$ of the order of a few tens of Schwarzschild radii $R_{\rm s} = 2GM/c^2$, where M is the black hole mass. The generic nature of the outflow characteristics at supercritical accretion rates [see e.g. equation (5) 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 PG 1211+143, Pounds et al. (2003) found a photospheric radius $R_{\rm ph} \sim 150 R_{\rm s}$ from their estimate of $\dot{M}_{\rm out}/\dot{M}_{\rm Edd}$. 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 $\dot{M}_{\rm out} v$ is of precisely the same order as the radiation momentum rate $L_{\rm Edd}/c$.

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, $R_{\rm ph}$ in terms of $\dot{M}_{\rm out}/\dot{M}_{\rm Edd}$.

2 OUTFLOWS FROM EDDINGTON-LIMITED ACCRETORS

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

$$\dot{M}_{\rm Edd} = \frac{4\pi G M}{\eta \kappa c}. \tag{1}$$

Here ηc^2 is the accretion yield from unit mass, and κ is the electron scattering opacity. We assume that the outflow is radial, in a double cone occupying solid angle $4\pi b$, 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

$$\rho = \frac{\dot{M}_{\rm out}}{4\pi v b r^2}. \tag{2}$$

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

$$\tau = \int_R^\infty \kappa \rho \, {\rm d}r = \frac{\kappa \dot{M}_{\rm out}}{4\pi v b R}. \tag{3}$$

From equations (1) and (3) we get

$$\tau = \frac{1}{2\eta b} \frac{R_{\rm s}}{R} \frac{c}{v} \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}}. \tag{4}$$

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Defining the photospheric radius $R_{\rm ph}$ as the point $\tau = 1$ gives

$$\frac{R_{\rm ph}}{R_{\rm s}} = \frac{1}{2\eta b}\frac{c}{v}\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}} \simeq \frac{5}{b}\frac{c}{v}\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}}, \tag{5}$$

where we have taken $\eta \simeq 0.1$ at the last step. Since $\leqslant 1$ and $v/c < 1$ we see that $R_{\rm ph} > R_{\rm s}$ for any outflow rate $\dot{M}_{\rm out}$ of the order of $\dot{M}_{\rm Edd}$, that is, such outflows are Compton-thick.

If instead $b \ll 1$, 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 $r = R_\perp$ where the optical depth across the flow

$$\tau_\perp \simeq \kappa\rho(r) b^{1/2} r \tag{6}$$

is of the order of unity. Thus

$$\frac{R_\perp}{R_{\rm s}} = \frac{1}{2\eta b^{1/2}}\frac{c}{v}\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}} \simeq \frac{5}{b^{1/2}}\frac{c}{v}\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm Edd}}, \tag{7}$$

and we again conclude that the outflow is Compton-thick for $\dot{M}_{\rm out} \sim \dot{M}_{\rm Edd}$.

This conclusion evidently implies that much of the emission from such objects will be thermalized and observed as a softer spectral component [see equation (18) below]. The observed harder X-rays must presumably either be produced near the 'skin' of the outflow (i.e. at moderate τ), or result from shocks within the outflow. In both cases their total luminosity must be lower than that of the thermalized soft component.

We now investigate how the outflow is driven. Since the wind is Compton-thick, most of the photons have scattered and thus on average given up their original momentum to the outflow. Outside the radius $R_{\rm ph}$ or $R_\perp$ the photons decouple from the matter and there is no more acceleration. This justifies our assumption that v is constant for large r, and it is self-consistent to use the assumption to integrate inwards to $R_{\rm ph}$ or $R_\perp$.

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

$$R_{\rm ph},\, R_\perp \simeq R_{\rm esc} = \frac{c^2}{v^2} R_{\rm s}. \tag{8}$$

From this equation and equations (5) and (7) we find

$$\frac{v}{c} \simeq \frac{2\eta f \dot{M}_{\rm Edd}}{\dot{M}_{\rm out}},\; R_{\rm ph,\perp} \simeq \left(\frac{\dot{M}_{\rm out}}{2\eta f \dot{M}_{\rm Edd}}\right)^2, \tag{9}$$

where $f = b, b^{1/2}$ in the two cases $b \lesssim 1, b \ll 1$. We can write these formulae more compactly as

$$\frac{v}{c} = \frac{2 f L_{\rm Edd}}{\dot{M}_{\rm out} c^2}, \tag{10}$$

$$\frac{R_{\rm ph,\perp}}{R_{\rm s}} = \left(\frac{\dot{M}_{\rm out} c^2}{2 f L_{\rm Edd}}\right)^2. \tag{11}$$

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

An immediate consequence of (10) is

$$\dot{M}_{\rm out} v = 2 f \frac{L_{\rm Edd}}{c}, \tag{12}$$

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 the order of v/c:

$$\dot{M}_{\rm out}\frac{v^2}{2} = \frac{v}{c} f L_{\rm Edd} = \frac{2(f L_{\rm Edd})^2}{\dot{M}_{\rm out} c^2}. \tag{13}$$

3 THE BLACKBODY COMPONENT

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

$$A_{\rm phot} = 4\pi b R_{\rm ph}^2. \tag{14}$$

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

$$A_\perp = 2\pi R_{\rm ph}^2 b^{1/2}. \tag{15}$$

We can combine these two cases as

$$A_{\rm ph,\perp} = 4\pi g \left(\frac{\dot{M}_{\rm out} c^2}{2 L_{\rm Edd}}\right)^4 R_{\rm s}^2, \tag{16}$$

with $g(b) = 1/b,\ 1/2b^{1/2}$ in the two cases. Again $g \sim 1$ unless $b \lesssim 10^{-2}$, 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

$$A_{\rm ph,\perp} = 2 \times 10^{29} g \dot{M}_1^4 M_8^{-2}\ {\rm cm}^2, \tag{17}$$

where $\dot{M}_1 = \dot{M}_{\rm out}/(1\ {\rm M}_\odot\ {\rm yr}^{-1})$ and $M_8 = M/10^8\ {\rm M}_\odot$. The effective blackbody temperature is

$$T_{\rm eff} = 1 \times 10^5 g^{-1/4} \dot{M}_1^{-1} M_8^{3/4}\ {\rm K}. \tag{18}$$

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

4 DISCUSSION

We have investigated supercritical accretion ($\dot{M} \gtrsim \dot{M}_{\rm Edd}$) 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 $\dot{M} \gtrsim \dot{M}_{\rm Edd}$ will show a strong Compton-thick outflow, with effective photosphere of size a few tens of $R_{\rm s}$, scaling as $\dot{M}_{\rm out}^2$. The outflow velocity is of the order of the escape velocity from this photosphere, and scales as $\dot{M}_{\rm out}^{-1}$. Observations of the QSO PG 1211+143 strongly support this picture.

In this picture much of the accretion energy must be emitted from the photosphere with typical temperature given by equation (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 $\dot{M} \gtrsim \dot{M}_{\rm Edd}$. The particular ULX discussed by Fabbiano et al. (2003) has a blackbody temperature of the order of 10^6 K, and equation (18) shows that a 10-${\rm M}_\odot$ black hole would need an outflow (and thus a mass transfer) rate of the order of $10\dot{M}_{\rm Edd} \sim 10^{-6}\ {\rm M}_\odot\ {\rm yr}^{-1}$. This is not extreme for thermal time-scale mass transfer in a massive X-ray binary ('SS433-like') or for a bright transient ('GRS 1915+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 et al., where it is noticeable that the blackbody luminosity remains constant while the temperature changes by factors of ~ 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 $\dot{M}_{\rm out}/\dot{M}_{\rm Edd}$ and thus the accretion rate through equation (10). Thus the $v = 0.27c$ jets seen in SS433 would imply a mass transfer rate $\sim 5\dot{M}_{\rm Edd}$. 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 $L_{\rm Edd}$. Interestingly, it is clear that the radiation pattern in the microquasar GRS 1915+104 [isotropic luminosity $\simeq 4L_{\rm Edd}$, cf. King (2002)] is indeed wider than the matter outflow, i.e. b(radiation) $>$ b(outflow). This would agree with the suggested radiation pattern for the case b(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 active galactic nuclei 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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