Black Holes from Stars to Galaxies – Across the Range of Masses
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Hyperaccretion

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Abstract. Accretion at rates exceeding the Eddington limit is common in close binaries. I summarize the arguments leading to the conclusion that such stellar–mass systems appear as ultraluminous X-ray sources when viewed close the the inner accretion disc axis, and like SS433 when viewed from other angles.

I show that AGN are unlikely to achieve electron–scattering Eddington ratios as high as ULXs, so there are few ULX analogues among quasars. However hyperaccretion of *dusty* matter is common among AGN. The resulting outflow naturally has a toroidal geometry, and may well be the origin of the dusty torus invoked in unified AGN schemes.

Keywords. Black hole physics – accretion, accretion discs – X-rays: binaries – galaxies: active

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1. Introduction

Accretion is the most efficient way of using normal matter to release radiant energy. The very first papers on the subject (e.g. Salpeter 1964) already recognised that radiation pressure imposes a natural limit on the accretion luminosity, usually expressed as the Eddington limit $L_{\rm Edd} \simeq 4\pi GMc/\kappa$, where κ is the opacity and M is the accretor mass. However there is no reason why the source of the accreting matter should know about this limit. This raises the obvious question of what happens in hyperaccreting systems, i.e. ones where the accretor is fed matter at rates $\dot M$ far above the value $\dot M_{\rm Edd} = L_{\rm Edd}/\epsilon c^2$ which would produce $L_{\rm Edd}$, where $\epsilon \sim 0.1$ is the efficiency. We note that for electron scattering opacity $\kappa \simeq 0.34$ we have $\dot M_{\rm Edd} \simeq 10^{-7}{\rm M_\odot}\ {\rm yr}^{-1}(M/10{\rm M_\odot})$.

2. Hyperaccreting binaries

This question is particularly acute for accreting binary systems, since here there are several generic situations in which mass transfer naturally proceeds at values $\gg \dot M_{\rm Edd}$. An extremely common case occurs when a massive early–type star fills its Roche lobe and transfers mass to a less massive accretor. All high–mass supergiant X-ray binaries will pass through this stage for example. It is easy to show (e.g. King & Ritter 1999) that the donor then transfers its mass M_2 mass to the accretor on its thermal timescale $t_{\rm KH}$, i.e. $\dot M = -\dot M_2 \sim M_2/t_{\rm KH}$, leading to rates $\dot M \sim 10^{-5} - 10^{-3}{\rm M_\odot}\ {\rm yr}^{-1}$ or more, i.e. $\dot M \gtrsim 10^2 - 10^4\dot M_{\rm Edd}$.

Such accretion rates mean that the accreting luminosity reaches the Eddington value even before the matter has fallen all the way down the accretor's gravitational potential well, that is, well above its surface. At this point radiation pressure must start to blow some of the accreting matter away, presumably self–limiting to the point that accretion within this point proceeds only at the (decreasing) Eddington rate corresponding to each radius. This is essentially the picture derived by Shakura & Sunyaev (1973), who call the critical point the spherization radius, with $R_{\rm sph} \sim (\dot M/\dot M_{\rm Edd})R_s$, where R_s is the accretor's Schwarzschild radius. This is essentially the same as the trapping radius defined by some other authors (e.g. Begelman 1979).

Near $R_{\rm sph}$ matter must be driven out in a dense, roughly spherical outflow. King & Begelman (1999) show that in most cases of thermal–timescale mass transfer the dense region near $R_{\rm sph}$ is still well away from interacting directly with the donor star, which might possibly trigger common–envelope evolution. Despite the highly supercritical mass transfer rate, the binary evolves in a fairly normal manner when we take account of the angular momentum lost in the outflow (cf King & Ritter 1999). Within $R_{\rm sph}$ the local accretion rate decreases roughly as $\dot M(R) \simeq \dot M_{\rm Edd}(R/R_{\rm sph})$, implying a total accretion luminosity

$$L_{\rm acc} \simeq L_{\rm Edd}\left(1 + \ln\frac{-\dot M_2}{\dot M_{\rm Edd}}\right) \qquad (2.1)$$

which can be as large as $\sim 10L_{\rm Edd}$ for mass transfer rates $-\dot M_2 \sim 10^4\dot M_{\rm Edd}$.

Clearly we would like to know how this thermal–timescale phase appears to observation. In particular one might imagine that it should have a fairly spectacular manifestation, given the high energies and prodigious outflows involved. Begelman, King & Pringle (2006) show that the answer depends on our viewing angle. If we observe the system from an angle close to the axis of the inner accretion disc (which is probably close to the spin axis of a black hole accretor) we see an ultraluminous X-ray source (ULX). These sources appear very bright partly because they are intrinsically somewhat super–Eddington (cf eqn 2.1), and also because this luminosity can only escape along the axis of the dense outflow. Given collimation solid angles $\Omega = 4\pi b$ with $b \sim 0.1$ we see that a $10{\rm M}_\odot$ black hole can have apparent luminosity $L \sim L_{\rm acc}/b \sim 10^{41}$ erg s^{-1}.

Interestingly, Begelman *et al.* (2006) did not set out to investigate ULXs, but reached this conclusion by considering the famous source SS433, which turns out to be what a hyperaccreting binary looks like when viewed 'from the side', i.e. away from the inner disc axis. Here the dense outflow obscures our view of the most energetic part of the accretion flow. Our only evidence for this in SS433 is the relativistic jets, which themselves carry mechanical energy $\gtrsim L_{\rm Edd}$. The clue allowing insight here is the fact that these precessing jets also show a nodding motion at one–half of the orbital period. This is clear evidence of the $m = 2$ tidal torque acting on the outer accretion disc. Begelman *et al.* (2006) show that the only plausible way of conveying this torque to the inner regions of the disc involved in jet formation is the dense outflow. The jet are presumably launched along the local disc axis, and the outflow imprints the long precession period and the nodding motion on them by deflecting them along the outflow axis, which already has these motions.

3. Hyperaccreting AGN

The last Section shows that the hyperaccretion problem is specified purely by $\dot M_{\rm Edd}$ and R_s. We can obviously extend all this work to hyperaccreting AGN. The major difference is that AGN have a much more limited Eddington factor, i.e. $\dot M/\dot M_{\rm Edd}$ does not attain such large values for AGN as for binaries. We can see this from a simple argument. Whatever process fuels the supermassive black holes in active galactic nuclei (e.g. minor mergers with small satellite galaxies) presumably feeds gas in dispersed form into orbit near the hole before it gets accreted. The maximum likely accretion rate then comes from assembling the largest gas mass which can orbit, and assuming that some triggering event causes it to fall freely on to the black hole.

We can assume that the host galaxy is roughly represented by an isothermal sphere of ‘gas’ (= all normal matter) and dark matter. Then the ‘gas’ mass inside radius R is

$$M_g(R) = \frac{2\sigma^2 R f_g}{G} \tag{3.1}$$

where σ is the velocity dispersion and f_g the gas fraction.

The highest plausible accretion rate is given by getting all this mass to fall inwards on the dynamical timescale R/σ, i.e.

$$\dot{M}_{\rm max} \simeq \frac{2\sigma^3}{G} f_g. \tag{3.2}$$

Note that this is independent of R. Now the black hole mass is related to σ by

$$M = \frac{f_g \kappa}{\pi G^2}\sigma^4 \tag{3.3}$$

(King 2003, 2005) which implies an Eddington luminosity for gas–rich matter

$$L_{\rm Edd} = \frac{4cf_g}{G}\sigma^4 \tag{3.4}$$

and thus an Eddington accretion rate

$$\dot{M}_{\rm Edd} = \frac{4f_g}{\epsilon G c}\sigma^4. \tag{3.5}$$

where ϵ is the accretion efficiency. Hence we get the Eddington ratio

$$r_E = \frac{\dot{M}_{\rm max}}{\dot{M}_{\rm Edd}} = \frac{\epsilon c}{2\sigma} \tag{3.6}$$

For typical values ($\epsilon = 0.1, \sigma = 150 M_8^{1/4}$ km s^{-1}) we have

$$r_E \sim 100 M_8^{-1/4} \tag{3.7}$$

where $M_8 = M/10^8{\rm M}_\odot$.

As it stands this argument concerns ‘grand design’ inflows occupying a major part of the galaxy. One might try to circumvent it with flows targeted within the black hole’s sphere of influence $R_i = 2GM/\sigma^2$, when the problem is more like Bondi accretion. However it is easy to show that this gives essentially the same limit. This $\sim \sigma^3/G$ limit probably always appears if the mass reservoir used for the accretion was in any kind of equilibrium with the host galaxy or the black hole before accreting. The most likely way around it is to bring in a mass reservoir which is is self–gravitating, like a star. If this can be disrupted very close to the hole one can presumably get higher $\dot{M}$.

Evidently in practice one rarely gets accretion at a rate $> \sigma^3/G$, and thus AGN Eddington ratios are generally modest (cf eqn 3.7). Since $r_E < 100$ the bolometric luminosity exceeds the formal $L_{\rm Edd}$ by $< \ln r_E \sim 4.6$. One would expect to see outflow at velocities $< c/r_E^{1/2} \sim 0.1c$, which is indeed about the maximum seen, e.g. in PG1211+143 (Pounds *et al.* 2003). It seems plausible that the collimation of the radiation by the outflow is weaker at such low r_E. Hence quasars probably only rarely appear very super–Eddington, i.e. there are few extreme ULX analogues among them.

4. The dusty torus

So far we have assumed (in eqn 3.4) that the accreting matter is gas, with electron scattering opacity κ. However at sufficient distance from the active nucleus there must be dusty matter, with opacity $\kappa_d > \kappa$. Then the local Eddington accretion rate is smaller by $k = \kappa/\kappa_d$, which can be $\sim 10^{-2}$, so that the effective r_E increases by $1/k$. This would give a dusty outflow with spherization radius

$$R_d \sim 500\,\frac{R_s}{k} \sim 5 \times 10^4 R_s = 0.5 M_8 \text{ pc}. \tag{4.1}$$

The radiation temperature of the AGN is

$$T_{\rm rad} \leqslant 3.5 \times 10^5 \,(l M_8)^{1/4} \left(\frac{R_s}{R}\right)^{1/2} \text{ K}, \tag{4.2}$$

where l is the (electron–scattering) Eddington ratio. If dust sublimates at 1200 K, the sublimation radius is at

$$R_{\rm sub} = 9 \times 10^4 \,(l M_8)^{1/2}\, R_s = 0.9 l^{1/2} M_8^{3/2} \text{ pc}. \tag{4.3}$$

Hence for $l^{1/3} M_8 < 1$ or so the dust survives.

Equations (4, 5) of Begelman *et al.* (2006) can now be used to show that the dust optical depth τ_d across the outflow increases by $1/k^{3/2}$ to values $\leqslant 2 \times 10^4$. It is clear that $\tau_d > 1$ even for quite modest amounts of matter near the AGN. We thus have a dusty outflow from typical radius R_d, which creates a natural toroidal geometry for the obscuring matter near the AGN. This appears to offer a natural explanation for the dusty torus invoked in unified AGN schemes (Antonucci 1993; Urry & Padovani 1995). Note that there is no reason to assume that the dusty torus must supply the matter needed to power the AGN. Indeed the very long viscous times at such large radii suggest that the latter probably results from an independent accretion flow on much smaller scales. Hence this geometry is likely to be similar in most AGN, regardless of their central accretion rates.

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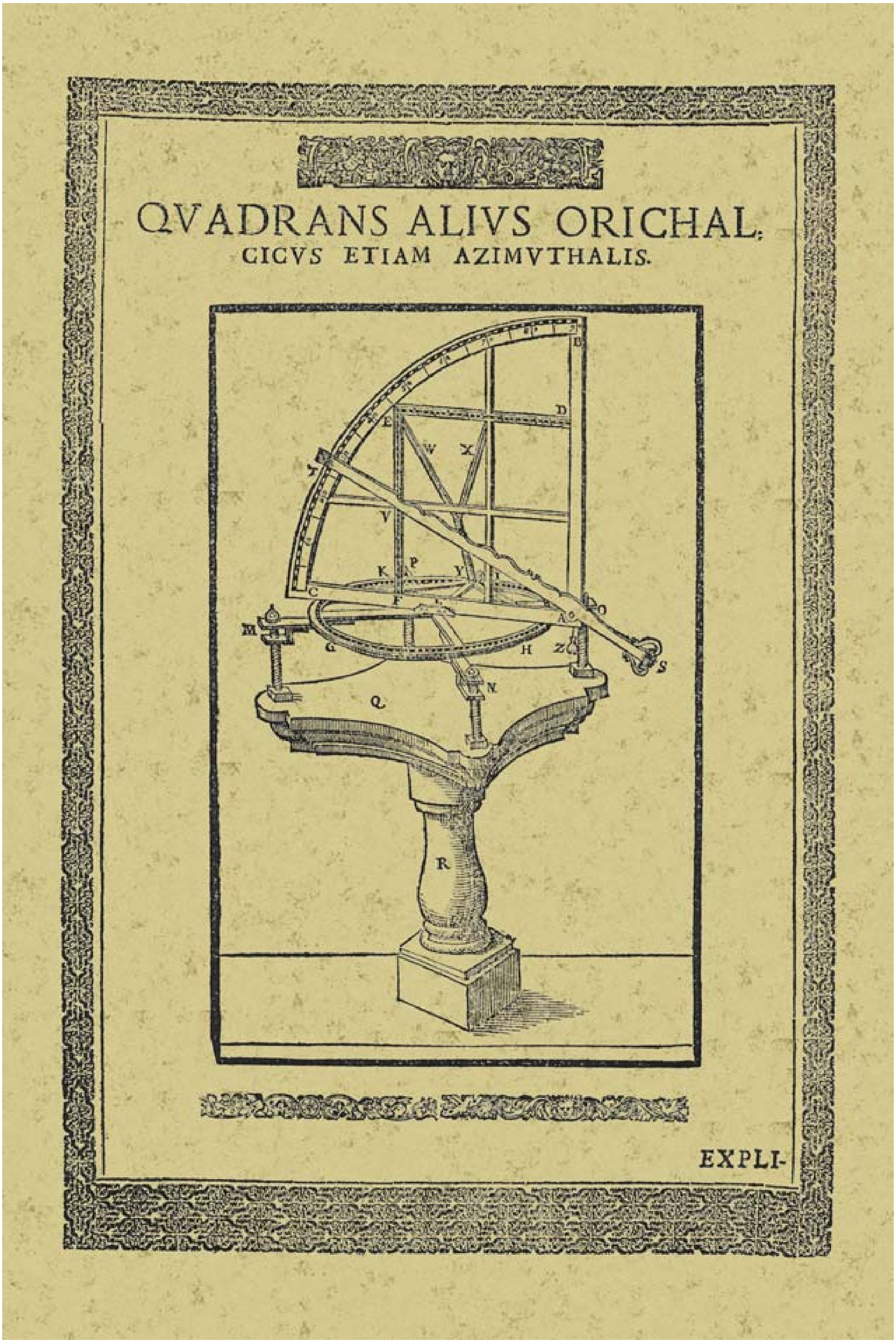
Mike Dopita: Comment: There is a lot of evidence to support radiation-pressure dominated outflows in dusty gas around AGN. For example NGC 1068 shows outflowing "comets" with velocity $\sim$ 2000 km/s. However, in AGN there may be two flows – a dusty one like you suggest, and an inner thermal flow like in SS443. Many of these (speculative) ideas were published in Dopita (1997, PASA, 14, 230) which emphasized super-Eddington outflows in the context of AGN.

Felix Mirabel: Is there a connection between hyper-accretion and the presence of hadrons in the jets of SS433?

Andrew King: I think it is possible that in the collision with the outflows the jets entrain a lot of material and are slowed down. So hyper-accretion tends to load the jets with baryons.

Fukun Liu: You suggest in your model that the outer part of the disc is affected by irradiation from the inner region. Do you have any observational evidence for it? Because it might seem more reasonable that the outer part of the disc is coplanar with the orbital plane and the inner part is warped due to Bardeen–Peterson effect.

Andrew King: No observational evidence; it is possible that the Bardeen–Petterson effect leads to the warp of the inner region of accretion disc. But the inner warped disc would become coplanar or flat on the several precessing timescales.



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