Black Hole Blackbodies

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ABSTRACT

Many black–hole sources emit a substantial fraction of their luminosities in blackbody–like spectral components. It is usual to assume that these are produced in regions at least comparable in size to the hole’s Schwarzschild radius, so that a measure of the emitting area provides an estimate of the black hole mass \( M \). However there is then no guarantee that the source luminosity (if isotropic) obeys the Eddington limit corresponding to \( M \). We show that the apparent blackbody luminosity \( L_{\text{sph}} \) and temperature \( T \) must obey the inequality

\[
L_{\text{sph}} < 2 \times 10^{44} (T/100 \text{ eV})^{-4} \text{ erg s}^{-1}
\]

for this to hold. Sources violating this limit include ultrasoft AGN and some of the ultraluminous X–ray sources (ULXs) observed in nearby galaxies. We discuss the possible consequences of this result, which imply either super–Eddington or anisotropic emission in both cases. We suggest that the ultrasoft AGN are the AGN analogues of the ULXs.

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

1 INTRODUCTION

Many luminous accreting sources have prominent spectral components which appear approximately blackbody. If the accretor is a black hole it is natural to assume that the dimensions of the emitting surface are comparable to the Schwarzschild radius, as this is the region where most of the gravitational potential energy is released. However the result of this procedure is not necessarily compatible with the Eddington limit on the source luminosity, derived from the requirement that the radiation pressure should not drive the accreting matter away. Examples of this for quasars have appeared in the literature (Puchnarewicz, 1994; Molthagen, Bade and Wendker 1998; Puchnarewicz 1998). Here we investigate the question systematically, and show that various classes of accreting black holes do not straightforwardly correspond to sub–Eddington blackbodies. In general the resolution of this difficulty appears to require super–Eddington or anisotropic emission.

2 BLACKBODIES

The luminosity and effective temperature of an optically thick emission region of typical size \( R \) near a black hole are related by

\[
L = 4\pi p \sigma R^2 T^4
\]

where the factor \( p \) allows for deviations from isotropy and spherical symmetry in both source geometry and emission pattern. We write \( R = r R_s \), where \( R_s = 2GM/c^2 \) is the Schwarzschild radius, so that

\[
L = \frac{16\pi \sigma c^2}{c^3} pr^2 M^2 T^4.
\]

We can also express \( L \) in terms of the Eddington value \( L_{\text{Edd}} \), as

\[
L = \frac{4\pi GM m_p c}{\sigma T},
\]

with \( l = L/L_{\text{Edd}} \). If the emission is anisotropic we must be careful to distinguish between the true luminosity \( L \) and the ‘spherical’ value \( L_{\text{sph}} \) assigned by a distant observer. As the translation from observed flux to luminosity generally assumes isotropic emission these are related by

\[
L = b L_{\text{sph}}.
\]

Here \( b \leq 1 \) if (as expected in a flux–limited sample) the observer lies within the ‘beam’ of the source (note that ‘beaming’ here merely means ‘anisotropic’, and does not necessarily imply relativistic beaming). Eliminating \( M \) between (2) and using the definition of \( L_{\text{sph}} \) we get

\[
L_{\text{sph}} = \frac{L}{b} = \frac{2.3 \times 10^{44} l^2}{T_{100}^4 pr^2} \text{ erg s}^{-1},
\]

and thus

\[
M = 1.8 \times 10^6 \frac{l}{T_{100}} p^{-2} M_\odot,
\]

where \( T_{100} \) is \( T \) in units of 100eV. Hence any object which violates the limit
must have $l^2/pbr^2 > 1$, i.e. must either be super–Eddington ($l > 1$), or emit from a region much smaller than the Schwarzschild radius ($r < 1$), or emit anisotropically ($p b < 1$). In the latter case, the luminosity $L$ will be less (by a factor up to $b$) than estimated at infinity by assuming isotropic emission. Given a choice of $l, p, r$ we get a mass estimate from (7). A simple interpretation of the limit (7) is that it ensures that the lower mass bound given by respecting the Schwarzschild radius ($p b = r = 1$). We can generalise this result to the case where the blackbody emission is not the only luminosity component detected, i.e., where (7) is replaced by

$$L = fL_1 + 4\pi prR^2T^4,$$ (8)

where $f$ is again a ‘beaming’ factor reflecting the difference between the real luminosity $fL_1$ and the value $L_1$ calculated by a distant observer assuming isotropic emission. For example, $fL_1$ might be the power–law continuum frequently observed. Then using $R = rR_s$ and (7) as before we get

$$fL_1 = -\frac{pr^2}{F^2}L^2 + L.$$ (9)

Since $L_1 > 0$ we have

$$L < L_0 \frac{l^2}{pr^2},$$ (10)

and maximizing the rhs of (7) as $L$ varies implies

$$L_{1, sph} = b^{-1}L_1 < L_0 \frac{l^2}{4pfr^2}.$$ (11)

Hence if (7) is violated, where $L_{sph}$ is now interpreted as the total luminosity, not that of the blackbody component alone, we can draw the same conclusions as before, i.e. that the whole source is either super–Eddington, or the blackbody component comes from a region smaller than the Schwarzschild radius or is emitted anisotropically. The main importance of this result is the implication that our conclusions above for the blackbody component alone (and the corresponding mass) are not affected by inaccuracies in subtracting a diluting non–blackbody component. The new feature is that these same conclusions must hold (with the possible alternative of beaming of the diluting continuum, i.e. $f < 1$) if the non–blackbody emission appears to violate the limit

$$L_{1, sph} < 0.25L_0 = \frac{6 \times 10^{43}}{T_{100}^4} \text{ erg s}^{-1}.$$ (12)

In principle this gives a formally tighter mass limit

$$M < \frac{4.4 \times 10^5}{T_{100}^4} \frac{l}{pr^2} M_\odot.$$ (13)

The main restriction on using these limits more widely is of course the difficulty of making accurate temperature determinations if the dilution is severe.

### 3 ‘SUPER–EDDINGTON’ SOURCES

The condition (7) divides sub–Eddington sources from those where more complex phenomena occur. Sources respecting this limit can be sub–Eddington; sources above it are either super–Eddington, or emit from a surface smaller than the black hole horizon, or emit anisotropically. Fig. 1 shows the limit plotted for a range of luminosities and temperatures covering both stellar–mass and supermassive systems.

#### 3.1 Stellar–mass black holes

For stellar–mass systems it is convenient to rewrite (7) as

$$L_{sph} = 1.4 \times 10^{39} \left(\frac{T}{2 \text{ keV}}\right)^{-4} \frac{l^2}{pbr^2} \text{ erg s}^{-1}$$ (14)

and

$$M = 10 \left(\frac{T}{2 \text{ keV}}\right)^{-4} \frac{l}{pr^2} M_\odot.$$ (15)

These forms agree with the well–known facts that X–ray bursters ($L_{sph} \lesssim 2 \times 10^{38} \text{ erg s}^{-1}, T \lesssim 2 \text{ keV}$) radiate isotropically ($p b \approx 1$) at close to the Eddington limit ($l \approx 1$) and are neutron stars ($r \approx 3$) with mass $M \lesssim 1.4M_\odot$. Outbursting soft X–ray transients reach luminosities $L_{sph} \gtrsim 10^{39} \text{ erg s}^{-1}$, but are generally ultrasoft, and so do not threaten the limit (7). They are therefore consistent with the Eddington limit for black–hole masses $\sim 5–10M_\odot$. Some of the ULX sources (see below) which appear to violate the limit may however be unrecognised transients.

#### 3.2 Ultraluminous X–ray sources (ULXs)

The ULXs are by definition a group of non–nuclear sources in nearby galaxies where the solar–mass Eddington limit is apparently violated, i.e. $L_{sph} \lesssim 10^{38} \text{ erg s}^{-1}$ (e.g. Makishima et al., 2000). We see from Fig. 1 that the ULXs straddle the line $L_{sph} = L_0$, potentially allowing an interpretation as sub–Eddington sources in some cases. However for $T \lesssim 2 \text{ keV}$ the required black–hole mass exceeds $10M_\odot$ (cf eq. 7). This led initially to claims that these objects had masses intermediate between stellar values and supermassive ones. However it hard to reconcile this idea with the clear link with recent star formation shown by Chandra observations of the Antennae (Fabbiano, Zezas & Murray, 2001) which reveal $\gtrsim 10$ ULXs. A more likely possibility is that most (if not all) ULXs involve beamed, and possibly transient, emission from a shortlived luminous phase of massive X–ray binary evolution (King et al., 2001). In any case, several of these sources violate the limit (7) as their temperatures are too high for the assigned ‘intermediate’ masses (cf eq. 13). Recognising this, Makishima et al (2000) suggested that their accretion discs extended very close to the horizon of a maximally rotating Kerr black hole ($r \sim 0.5$). Given the errors this may make all ULXs compatible with the $L_{sph} < L_0$ constraint, although only marginally.

#### 3.3 Ultrasoft quasars

The soft X–ray excess in AGN (i.e. an excess of $\sim 0.1–0.5 \text{ keV}$ flux above an extrapolation of the $\sim 2–10 \text{ keV}$ emission)
continuum) is believed to be the high energy tail of an accretion disc spectrum (Arnaud et al. 1995; Pounds et al., 1987; Turner & Pounds 1989; Masnou et al. 1994). A spectral turnover in soft X-rays that would fix an effective temperature for an accretion disc is rarely observed however, implying relatively cool discs. An upper limit on the disc temperature can be derived from the slope of the soft X-ray continuum (cf (5, 6); see also Fig. 1). The solid line is the limit \(L_{\text{Edd}} \approx L_0\). Sources below this line are compatible with the Eddington, isotropy and size constraints \(l < 1, pb = r = 1\), but must have masses \(M\) respectively above and below the values given on the rh vertical and upper horizontal scales. The thin line represents a luminosity 100 times this limit.

with much higher luminosities. The ultrasoft X-ray component in E1346+266 (z=0.92) was confirmed by the ROSAT PSPC to have a rest-frame temperature of \(120^{+20}_{-60}\) eV (errors are a conservative 99 percent; Puchnarewicz, Mason & Cordova 1994). With an intrinsic luminosity of \(~5 \times 10^{46}\) erg s\(^{-1}\) (assuming unbeamed, spherically symmetric emission), this corresponds to more than 100 times the Eddington limit. The three AGN from Puchnarewicz (1998) have rest-frame blackbody temperatures of \(~150\) eV and luminosities between \(2 \times 10^{44}\) erg s\(^{-1}\) and \(10^{45}\) erg s\(^{-1}\); the order of 10 times “super-Eddington” (see Fig. 1). A further eight hot (k\(T_{\text{BB}} \sim 100\) eV), high-luminosity \((L_{\text{sph}} \sim 3 \times 10^{44} - 10^{46}\) erg s\(^{-1}\)) candidates have been identified as part of the Einstein UltraSoft Survey (USS; Puchnarewicz et al. 1992; Cordova et al. 1992; Thompson & Cordova, 1994), although further data would be required to confirm the soft spectra indicated by Einstein.

There has been evidence to suggest that the velocities of the broad line regions (BLRs) in AGN may provide an alternative way of measuring the black hole mass (see eg. Laor 1998). However, four of the six high-luminosity quasars discussed in Puchnarewicz (1998) have slow BLRs, which would seem to refute this relationship. A simple way of addressing this is to invoke anisotropy in the continuum emission, which would reduce the black hole mass and the broad line region velocity. However, this involves several naive assumptions about the relation between the black hole mass, accretion disc spectrum and the conditions, geometry and velocity of the BLR. We caution that while supporting our hypothesis of anisotropy in ultrasoft quasars, this solution may not be as straightforward as it appears; we postpone further discussion to future work. The more fundamental issue of apparently super-Eddington emission from quasars remains, irrespective of the conditions in the BLR.

4 DISCUSSION

**Figure 1.** Luminosity and blackbody temperature for bright X-ray blackbody sources. Filled diamonds are confirmed ultrasoft AGN, E1346+266 is labelled separately and errors on the blackbody temperature are 99 percent. Open diamonds are confirmed ultrasoft AGN. E1346+266 is labelled separately and errors on the blackbody temperature are 90 percent. Open squares are confirmed ULXs (E1346+266 is labelled separately and errors on the blackbody temperature are 99 percent). The other three are ROSAT AGN. Filled squares are confirmed ULXs. Also plotted individually are the remaining high-z USS AGN. Also plotted individually are the remaining high-z USS AGN. Also plotted individually are the remaining high-z USS AGN. Also plotted individually are the remaining high-z USS AGN.

Fig. 1 shows that the ultrasoft AGN have luminosities \(L_{\text{sph}}\) a factor \(~10 - 30\) above the value of \(L_0\) appropriate to their measured temperatures, while several ULX sources show a similar if smaller effect. Before going further we should check if these results could be spurious. Probably the most serious possible cause of error arises from the claimed blackbody temperatures. These might be systematically too high either because (a) the values of \(T\) are wrongly fitted, or (b) the spectra are not blackbody at all, but for example the result of Comptonization, or the effects of electron scattering in regions with low absorption opacity. Errors of the right order (factors \(\lesssim 3 - 10\)) appear unlikely; and if the effect is a physical one we have to explain why it occurs only in a subset of AGN. Nevertheless this area merits further study.

If we accept the values of \(T\) appearing in Fig. 1, we should consider the possibility that the emission may come from a region of total area smaller than the Schwarzschild radius \(R_s\), i.e. that \(r < 1\). Since most of the accretion energy is released in a region of order \(R_s\), this requires that it should be removed non-radiatively, and only converted to radiation in a much smaller region. The only way of ensuring this appears to involve magnetic fields. Merloni & Fabian (2001) have indeed suggested that magnetic reconnection in regions comparable with the local disc thickness \(H\) may be
the primary dissipation mechanism in accretion discs. However, they also require that these regions should be triggered at heights at least an order of magnitude larger than their size. Since \( H \sim 0.1R \), heights \( > \sim R > \sim R_s \) are needed.

In this picture, blackbody emission would result from reprocessing the primary emission from these 'lamppost' regions on the disc surface. The reprocessing regions cannot be smaller than the lamppost heights \( > \sim R_s \), implying \( r > 1 \) in this model. Similar considerations probably apply in other magnetic energy release pictures.

Thus assuming that the values of \( T \) in Fig. 1 are not grossly in error, and that the radiating regions of the sources are unlikely to be significantly smaller than their Schwarzschild radii, we are left with the alternatives that the sources with \( L_{\text{sph}} > L_0 \) are genuinely super–Eddington, or radiate anisotropically. We note that either of these possibilities would probably remove the need for intermediate masses \( M \gtrsim 100M_\odot \) in even those ULXs which do not violate the limit \( L_{\text{sph}} > L_0 \). Begelman (2002) has proposed a mechanism allowing thin accretion discs to radiate at up to ten times the Eddington limit, while King et al. (2001) have suggested that most ULXs are anisotropic emitters.

The common feature here is that presumably both types of source are supplied with mass at rates close to or above the Eddington value \( \dot{M}_{\text{Edd}} \approx L_{\text{Edd}}/0.1c^2 \). To zeroth order we would expect the resulting accretion geometry to be similar in the two cases despite the large difference in black hole mass. We therefore suggest that the ultrasoft AGN are the supermassive analogues of the ULXs.

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