On the observed disc temperature of accreting intermediate mass black holes

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\textbf{ABSTRACT}

Some ultraluminous X-ray sources in nearby galaxies show soft components resembling thermal disc emission. Calculations based on blackbody emission then indicate that the accreting black holes at the centres of these discs have masses of 100s to 1000s $M_\odot$. Establishing the existence of such intermediate mass black holes is of considerable importance so the assumptions and approximations lying behind blackbody spectral fits must be examined. We study here the basic assumption that the thermal emission is well-characterised by a multi-temperature blackbody spectrum. Since the opacity in the surface layers of a disc decreases at high energies the emergent spectrum is hardened. We compute the observed spectra from discs around a non-spinning 1000 $M_\odot$ black hole and fit them over the XMM-Newton pn band with multi-colour disc models. The typical overall spectra hardening factor usually adopted for discs around stellar mass black hole (assuming an inclination of 60 deg and including relativistic effects for a non-spinning black hole) is found to be appropriate.

\textbf{Key words:} galaxies:

\section{1 INTRODUCTION}

X-ray imaging of nearby galaxies often reveals the presence of off-nucleus Ultra-Luminous X-ray sources (ULX for short) with X-ray luminosities exceeding $10^{39}$ erg s\textsuperscript{-1} (for reviews see Fabiano & White 2003; Miller & Colbert 2003). Some have X-ray luminosities of several times $10^{40}$ erg s\textsuperscript{-1}. The variability of some ULX indicates that they are single objects, most likely a form of accreting black hole. The high luminosity, after a reasonable bolometric correction, exceeds the Eddington limit for 20 $M_\odot$, requiring a black hole of mass above that expected from the collapse of normal massive stars. The black hole mass inferred from the Eddington limit applied to the more luminous objects is $\sim 500 - 1000 M_\odot$ and exceeds that of the most massive stars known.

The possibility that such Intermediate Mass Black Holes (IMBH) exists is intriguing and raises questions about their origin and growth. Two main scenarios have been proposed; the first considers them to be remnants of the first stellar generation, Population III (Madau & Rees 2001), the second has them form recently by the merger of stellar-mass black holes in a star cluster (Portegies Zwart et al 2004). The IMBH hypothesis is supported by the observation of giant optical bubble nebulae around some ULX (Pakull & Mironi 2002) and by X-ray spectral evidence that some show evidence of cool accretion discs, consistent with them being simply accreting black holes like Cyg X-1 in its high state, scaled up in mass (Miller et al 2003, 2004. Dewangan et al 2004; Cropper et al 2004). Strohmayer & Mushotzky (2003) have moreover found an iron line in the spectrum of the ULX in M82.

Alternative hypotheses have been proposed. The first considers that the emission is anisotropic. This can result from either collimation at the source (King 2002) or relativistic beaming in a jet (Reynolds et al 1997; ref). The other hypothesis proposes that super-Eddington accretion is possible, i.e. that accretion can result in a super-Eddington X-ray luminosity at infinity (e.g. Begelman 2002). Of course the ULX population need not be homogeneous and all hypotheses may be represented by actual objects.

Here we remove one concern about the IMBH hypothesis. This is that the correction factor applied to the thermal radiation from the accretion disc to account for the high-energy tail departing from a perfect blackbody spectrum taken from calculations for stellar mass objects (Shimura & Takahara 1994; Merloni, Ross & Fabian 1999), might not apply to IMBH. The high energy tail is the most detectable part of the disc spectrum and is due to departures from a blackbody spectrum at high photon energies by the innermost radii of the accretion disc (see Laor & Netzer 1989 for spectra expected from discs around supermassive black holes). The observed spectrum is typically fitted with a simple multi-colour disc (MCD) model appropriate for a blackbody disc (Mitsuda et al 1984) and the black hole mass inferred from the luminosity of that inner region, after the correction factor has been applied. The correction factor is calculated here using the same method as in the work of Merloni et al (1999). Model spectra have been computed using constant-density disc models. These have then been
used to create fake X-ray spectra over the appropriate energy range and then fitted with the MCD model. Our results show that current work has estimated the black hole masses correctly provided that they are non-spinning and have an inclination of about 60 deg. The required mass rises as the black hole spin rises and drops slightly as the inclination decreases.

2 METHOD

The calculation of the disc spectrum proceeds as described by Merloni et al. (2000) with central mass $M = 1000 \, M_\odot$. At each radius, $r$, along the disc, the emergent spectrum is calculated assuming that the gas is fully ionized and that the gas density and the dynamic heating rate are uniform with depth. The density of the gas and the thickness of the disc at that radius are given by the formulae of Merloni et al. (2000). The disc is assumed to be radiation-pressure dominated for radii less than $36 R_S$, $70 R_S$ and $100 R_S$ for accretion rates of 0.05, 0.10 and 0.20 times the Eddington limit, respectively. The dynamic heating rate is set so that the proper total emergent flux,

$$ F = \frac{3GM\dot{M}}{8\pi r^3} \left( 1 - \sqrt{\frac{3R_S}{r}} \right), \quad (1) $$

is produced (Shakura & Sunyaev 1973).

The radiative transfer and the vertical temperature structure at each radius are treated self-consistently, taking into account incoherent Compton scattering and free-free processes, as described by Ross & Fabian (1996). (We do not use the coherent-scattering approximation in any of our calculations.) Typical emergent spectra are computed for twenty annuli that cover the region $3 R_S \leq r \leq 200 R_S$ of the disc. The effects of relativistic blurring on the observed total spectrum are then calculated using the method of Chen, Halpern & Filippenko (1989) with inclination $i = 60^\circ$ assumed. An example is shown in Fig. 1.

3 RESULTS

We now estimate spectral correction factors with which to convert the results of spectral fitting of real data to physical parameters. The correction factors will depend on the energy band over which they are made and we therefore use that of the XMM-Newton EPIC pn CCD with which several of the soft ULX spectra have been measured. In order to do this we must fit our (blurred) model spectra with the multicolour disc model commonly used.

The three model spectra were therefore used to fake XMM-Newton pn spectral files which were then fitted over the 0.3–3 keV energy range with the models DISKBB (Fig. 2) and DISKPN. The results are shown in Table 1. The MCD model (DISKBB; Mitsuda et al 1984) assumes nothing about the inner boundary (there is no zero-torque boundary condition at the innermost stable orbit of $3 R_S$),

| Accretion rate | $kT_{in}$ (keV) DISKBB | $kT_{in}$ (keV) model | $f_0$ | $kT_{in}$ (keV) DISKPN | $\beta$ |
|---------------|----------------|-------------------|-----|----------------|----|
| 0.05          | 0.209         | 0.100             | 1.40| 0.199          | 1.28|
| 0.10          | 0.244         | 0.119             | 1.35| 0.233          | 1.24|
| 0.20          | 0.284         | 0.142             | 1.30| 0.271          | 1.19|

Table 1. Results from fitting simulated data from the 3 model spectra with the DISKBB and DISKPN MCD models. $f_0$ is the overall hardening factor required to convert the DISKBB normalization $K$ to $R_{in}$ (eqn. 3).

was produced (Shakura & Sunyaev 1973).

The black hole mass, $M_{BH}$, is routinely obtained from the normalization of the model, $K$, which essentially provides an estimate of the emitting area. For the DISKBB model the inner radius of the disc (assumed to be $6GM_{BH}/c^2$) is

$$ R_{in} = \eta g(i) D f^2 \sqrt{K/\cos i} \, \text{km}, \quad (2) $$

where $D$ is the distance to the source in units of 10 kpc. $\eta$ and $g(i)$ account for (a) the fact that the disc emission peaks outward of the innermost radius and (b) relativistic blurring and beaming effects, respectively. Values of $\eta \sim 0.5 - 0.7$, $g(i) \sim 0.7 - 0.9$ (Zhang, Cui & Chen 1997) and $f = 1.7$ (Shimura & Takahara 1994) are often used. We have however included these effects in our model so it is then appropriate to use $\eta g = 1$ and $\cos i = 0.5$, yielding the values of $f_0$ shown in Table 1, where our $f_0^2 = \eta g f^2$. Our general result is

$$ R_{in} = \frac{g(i)}{g(60^\circ)} D f_0^2 \sqrt{K/\cos i} \, \text{km}, \quad (3) $$

Miller et al (2003), for example, assumed $\eta = 0.63$ and $f = 1.7$ which combine to give an overall correction factor very close to our calculated correction factor $f_0 = 1.35$ for an accretion rate of 0.10 times the Eddington limit. Those observational results are therefore robust within the assumptions of our model.

The DISKPN model (Gierliński et al 1999) has a normalization defined so that

$$ M_{BH} = D \beta^2 \sqrt{K/\cos i}, \quad (4) $$

where the distance $D$ is in kpc and the spectral hardening factor is now denoted $\beta$. Values of $\beta$ deduced from our model fit are listed in Table 1.

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Figure 2. Predicted spectra, simulated with the XMM-Newton pn response, fitted with the simple multi-colour disc model DISKBB. The fake spectra are in the top panel and the ratio to the DISKBB model in the lower panel. Top figure: 0.05 Eddington, Middle: 0.1 Eddington and Lower: 0.2 Eddington.

4 DISCUSSION

We have shown that simple MCD models which assume blackbody spectra are a good fit in the XMM-Newton pn CCD band for the disc emission from accreting IMBH. The fitted inner-disc temperature is about a factor of two larger than the actual inner temperature. An overall spectral hardening factor of \( f_0 = \sqrt{\eta g f} \approx 1.35 \) is appropriate for estimating the black hole mass from the normalization of the spectral fit. The masses reported from recently modelling of the observed soft X-ray spectra of some nearby ULX are robust provided that the observed inclination is about 60 deg. The required mass decreases slightly if the inclination is smaller than this.

The hard tail to the disk spectrum is mostly the result of the surface layers of the inner disc becoming optically thin at higher energies. Photons from deeper, hotter, subsurface regions escape leading to more high energy emission than expected from a blackbody at the surface temperature. Comptonization tends to slightly reduce this tail due to scattering in the intervening regions between the photon source and the surface (Ross et al 1992). Remarkably, the spectral correction factor for XMM-Newton CCD spectra over the 0.3–3 keV range found here for 1000 M\(_\odot\) black holes is similar to that found for RXTE spectra in the 2–20 keV band for 10 M\(_\odot\) black holes. Further effects such as more dissipation in the outer layers will increase the hard tail making the correction factor larger.

Our results confirm that the detection of cool accretion discs in ULX is strong evidence that they contain IMBH.

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