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Accretion rates and beaming in ultraluminous X-ray sources

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ABSTRACT

I show that extreme beaming factors b are not needed to explain ultraluminous X-ray sources (ULXs) as stellar-mass binaries. For neutron-star accretors, one typically requires $b \sim 0.13$, and for black holes almost no beaming ($b \sim 0.8$). The main reason for the high apparent luminosity is the logarithmic increase in the limiting luminosity for super-Eddington accretion. The required accretion rates are explicable in terms of thermal-time-scale mass transfer from donor stars of mass 6–10 $M_{\odot}$, or possibly transient outbursts. Beaming factors $\lesssim 0.1$ would be needed to explain luminosities significantly above $10^{40} L_{40}$ erg s^{-1}, but these requirements are relaxed somewhat if the accreting matter has low hydrogen content.

Key words: accretion, accretion discs – black hole physics – binaries: close – X-rays: binaries.

1 INTRODUCTION

The nature of the ultraluminous X-ray sources (ULXs) is still not definitively settled. In one view, they are intermediate-mass black holes (IMBH) accreting at rates below their Eddington limits. In this Letter, I will adopt the contrary view (cf. King et al. 2001) that they represent a very bright and unusual phase of X-ray binary evolution, in which the compact object is fed mass at a rate $\dot{M}$ well above the usual Eddington rate $\dot{M}_{\rm E}$. In this picture, the large apparent X-ray luminosity $L_{\rm X} = 10^{40}\, L_{40}$ erg s^{-1} is a result of two effects (see below). First, the bolometric luminosity genuinely exceeds the usual Eddington limit by a factor of $\ln(\dot{M}/\dot{M}_{\rm E})$, which can be significant. Second, the X-rays may be collimated by a factor of b by scattering within an optically thick biconical outflow. These conditions could in principle reflect a genuine state of high mass transfer, or a transient outburst (King 2002). Comparing this picture with observation is currently complicated by the fact that there is freedom in choosing both the super-Eddington factor $\dot{M}/\dot{M}_{\rm E}$ and the beaming factor b.

In several ULXs, it is possible to identify a soft X-ray component, and indeed infer a lengthscale $R \sim 10^9$ cm associated with it. I show here that in the context of the adopted model for ULXs, this quantity and $L_{\rm X}$ essentially fix both the Eddington and beaming factors for a given mass M_1 of the accretor.

2 SUPER-EDDINGTON ACCRETION

An accretor supplied with mass at a super-Eddington rate arranges to expel matter from its accretion disc in such a way that it never exceeds the local Eddington luminosity (Shakura & Syunyaev 1973; cf. Begelman, King & Pringle 2006; Poutanen et al. 2007). In this picture, there is a characteristic lengthscale $R_{\rm sph}$ where the mass inflow first becomes locally Eddington (also called the spherization or trapping radius) (cf. Begelman et al. 2006, equation 14). Following Shakura & Syunyaev (1973), we write

$$R_{\rm sph} = \frac{27}{4}\frac{\dot{M}}{\dot{M}_{\rm E}} R_{\rm s}, \tag{1}$$

where $R_{\rm s} = 2GM_1/c^2 = 3 \times 10^5 m_1$ cm is the Schwarzschild radius of the accretor.

The nature of the accretion flows outside and inside this radius differs markedly. The region outside $R_{\rm sph}$ releases accretion luminosity $\sim L_{\rm E}$ in the usual way, where $L_{\rm E} = 1.6 \times 10^{38} m_1$ is the Eddington luminosity (for hydrogen-rich material). But at and within $R_{\rm sph}$, radiation pressure drives an outflow which keeps the local energy release very close to the Eddington value and creates a biconical geometry, collimating the outgoing radiation. This region releases a bolometric luminosity

$$L_{\rm acc} \simeq L_{\rm E}\left[1 + \ln\left(\frac{\dot{M}}{\dot{M}_{\rm E}}\right)\right]. \tag{2}$$

Because of the geometric collimation by a factor $1/b \geqslant 1$, an observer viewing such a disc in directions within one of the cones sees an *apparent* bolometric luminosity

$$L \simeq \frac{L_{\rm E}}{b}\left[1 + \ln\left(\frac{\dot{M}}{\dot{M}_{\rm E}}\right)\right] \tag{3}$$

(cf. Shakura & Syunyaev 1973; Begelman et al. 2006). The enhancement of L over $L_{\rm E}$ by beaming and the logarithmic factor is the basis of the interpretation of ultraluminous X-ray sources (ULXs) as hyperaccreting stellar-mass binaries (Begelman et al. 2006; Poutanen et al. 2007).

Because the accretion flow within $R_{\rm sph}$ is optically thick, the disc region there must produce a soft blackbody component (by reprocessing of harder radiation, if for no other reason). This must have characteristic lengthscale $R_{\rm sph}$ and luminosity $L_{\rm bb} \gtrsim L_{\rm E}$. This is only a part of the accretion luminosity (2), the harder power-law-like

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component characteristic of ULXs resulting from some other process such as comptonization or direct release of accretion energy. The observability of the soft blackbody component depends on its temperature $T = (L_{\rm bb}/4\pi\sigma R_{\rm sph}^2)^{1/4}$, which for typical ULX parameters $L_{\rm bb} \sim 10^{39}$–10^{40} erg s^{-1}, $R_{\rm sph} \sim 10^8$–10^9 cm is always in the range 0.1–1 keV. Several ULXs are observed to show such components, and it is reasonable to infer that more would do so if their temperatures were slightly higher or the photoelectric absorption slightly lower.

This interpretation of the blackbody component implies that it should be collimated by a similar beaming factor b to the harder radiation, and accordingly is likely to dominate the similar but unbeamed component produced outside $R_{\rm sph}$. Accordingly, we have to consider the effect of beaming on this component.

Since the inferred blackbody temperature $T \sim 0.1$ keV is determined by the spectral shape, and thus unaffected by collimation, the observer infers a total blackbody luminosity

$$4\pi R^2\sigma T^4 = \frac{4\pi}{b}R_{\rm sph}^2\sigma T^4 \tag{4}$$

from this component. Thus, we have $R_{\rm sph} = b^{1/2}R$. From equation (1), we find the Eddington ratio

$$\frac{\dot M}{\dot M_{\rm E}} = \frac{4R_{\rm sph}}{27R_{\rm s}} = \frac{490R_9b^{1/2}}{m_1}. \tag{5}$$

From equation (3), we finally deduce

$$b = \frac{0.016m_1}{L_{40}}\left[1+\ln\left(\frac{490R_9}{m_1}b^{1/2}\right)\right]. \tag{6}$$

We note that this equation uses the assumption that the characteristic lengthscale of the blackbody component is $R_{\rm sph}$, but does not assume that this component necessarily dominates the bolometric emission there.

Given a value of m_1, equation (6) is a transcendental equation for b. One can show by standard methods that it always has two roots for b unless m_1 is very large ($\gtrsim 3300R_9^2/L_{40}$). For typical ULX parameters, one root is small, of the order of 10^{-4}, while the other is in the range $b \sim 0.1$–1. For the small root, the logarithm on the RHS is small, implying $\dot M/\dot M_{\rm E} \sim 1$, while for the root close to unity the logarithm is $O(1)$, so that $\dot M/\dot M_{\rm E} \gg 1$.

Physically, these roots correspond respectively to two different possible cases. For the small root case, collimation dominates the logarithmic increase in the total accretion luminosity above the standard Eddington value, and is thus the main reason for the high apparent luminosity of the ULX. Hence, this case corresponds to an only mildly super-Eddington flow nevertheless producing a highly anisotropic radiation pattern. In the case where b is close to unity, collimation is weak, and the system appears bright largely because of the logarithmic increase in the true accretion luminosity. This latter case appears physically more plausible, and I will adopt the larger root for b in what follows. I consider masses $m_1 = 1.4$, 10 corresponding to a neutron-star and black hole accretor, respectively, and ask what values of b and $\dot M$ these require for two typical observed cases. (Note that all the formulae above hold for accretion on to a neutron star, or indeed any other star, provided only that it is sufficiently super-Eddington that its physical radius is smaller than the spherization radius $R_{\rm sph}$ defined in (1). Of course, if some of the accretion luminosity is emitted from the surface of the star, this could modify the relation between accretion rate and luminosity and slightly change the factor 27/4 in equation (1).)

2.1 Typical ULX, $L_{40} = R_9 = 1$

Taking $\dot M_{\rm E} = 2.5\times10^{-8}m_1$ M$_\odot$ yr^{-1}, corresponding to hydrogen-rich accretion with a radiative efficiency of $0.1c^2$, we find consistent solutions with

$$m_1 = 1.4,\quad b = 0.13,\quad \dot M/\dot M_{\rm E} = 125,\quad \dot M = 3.1\times10^{-6}\,{\rm M_\odot\,yr^{-1}} \tag{7}$$

and

$$m_1 = 10,\quad b = 0.76,\quad \dot M/\dot M_{\rm E} = 43,\quad \dot M = 1.0\times10^{-5}\,{\rm M_\odot\,yr^{-1}}. \tag{8}$$

2.2 Hydrogen-poor accretion

If the accreting matter has little hydrogen, the change in mean mass per electron alters (6) to

$$b = \frac{0.028m_1}{L_{40}}\left[1+\ln\left(\frac{490R_9}{m_1}b^{1/2}\right)\right] \tag{9}$$

and the Eddington accretion rate for efficiency $0.1c^2$ becomes $\dot M_{\rm E} = 4.2\times10^{-8}m_1$ M$_\odot$ yr^{-1}.

Then, if a neutron-star ULX accretes such matter we find

$$m_1 = 1.4,\quad b = 0.24,\quad \dot M/\dot M_{\rm E} = 171,\quad \dot M = 1.0\times10^{-5}\,{\rm M_\odot\,yr^{-1}}. \tag{10}$$

A black hole ULX ($m_1 = 10$) with $R_9 = 1$ accreting this kind of matter actually produces a luminosity $L = 1.36\times10^{40}$ erg s^{-1} without any beaming at all (i.e. $b = 1$) if it accretes with

$$m_1 = 10,\quad b = 1,\quad \dot M/\dot M_{\rm E} = 49,\quad \dot M = 2.0\times10^{-5}\,{\rm M_\odot\,yr^{-1}}. \tag{11}$$

For a very bright ULX with $L_{40} = 10$, $R_9 = 1$ accreting hydrogen-poor matter, we find

$$m_1 = 10,\ b = 0.10,\ \dot M/\dot M_{\rm E} = 16\text{and}\ \ \dot M = 6.7\times10^{-6}\,{\rm M_\odot\,yr^{-1}}. \tag{12}$$

3 DISCUSSION

The simple calculations of Sections 2.1 and 2.2 above illustrate the following general points.

(i) Extreme beaming factors are not needed to explain ULXs as stellar-mass binaries. With neutron stars, one typically requires $b \sim 0.13$, and with black holes almost no beaming ($b \sim 0.8$) except for the very brightest ULXs ($L_{\rm X} = 10^{41}$ erg s^{-1}). Here, beaming approaches 10 per cent, since $\ln(\dot M/\dot M_{\rm E})$ cannot realistically exceed 10, and $L_{\rm E}$ is similarly limited to a few times 10^{39} erg s^{-1}.

(ii) Typical ULXs with $L_{\rm X} = 10^{40}L_{40}$ erg s^{-1} and $R \simeq 10^9$ cm can be explained in either of the two ways:
neutron-star binaries accreting at ∼100 times their Eddington rates, i.e. at $\dot M \sim 3\times10^{-6}$ M$_\odot$ yr^{-1},
or black hole binaries accreting at ∼40 times their Eddington rates, i.e. at $\dot M = 1.0\times10^{-5}$ M$_\odot$ yr^{-1}.
I note that both required accretion rates are explicable in terms of thermal-time-scale mass transfer. This occurs when a high- or intermediate-mass radiative star transfers mass to a less massive companion, and gives rates $\dot M \sim 3\times10^{-8}m_2^{2.6}$ M$_\odot$ yr^{-1}, where m_2 is the companion mass in M$_\odot$ (King & Begelman 1999). We thus require companion masses $M_2 \gtrsim 6$ M$_\odot$, 10 M$_\odot$ in the neutron-star and black hole cases, respectively, with black hole masses slightly

greater than $10\,M_\odot$. As emphasized by King et al. (2001), this type of binary evolution predicts source lifetimes and numbers in good agreement with observation. Some very bright transients may be able to achieve these accretion rates during outbursts (cf. King 2002). This is likely to be the only way of making ULXs in old stellar populations (King et al. 1997).

(iii) Accretion of hydrogen-poor matter generally reduces the requirements for beaming still further, and is the most likely explanation for the very brightest ULXs ($L_X = 10^{41}\ L_{41}\ \mathrm{erg\,s^{-1}}$). Accretion from massive Wolf–Rayet type companions is most likely the origin of these very high luminosities, although other explanations are possible in rare cases (cf. King & Dehnen 2005).

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