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Are Ultra Luminous X-Ray Sources Microblazars ?

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Abstract. ROSAT and Chandra-observations have discovered several ultra-luminous X-ray sources (ULXs) exceeding luminosities of 5×10^{39}erg/s. Assuming isotropic emission, these sources should obey the Eddington limit, requiring the existence of intermediate-mass black holes of 20-500 $M_{\odot}$. However, the measured inner disk temperatures are too high for these masses and there is no convincing creation mechanism known for these objects. Recently, Markoff, Falcke, Fender (2001) suggested that jets could be dominantly contributing to the hard X-ray emission from X-ray binaries (XRB) at least in the Low/Hard State, meaning that some X-ray sources could be beamed. A beaming model would reduce the required black hole masses for ULXs to normal values. To test the hypothesis of beamed emission we consider a simple population synthesis model for XRBs, where the X-ray emission is produced by both a jet (beamed) and an accretion disk (isotropic). The model is tested on a combined dataset of X-ray point sources of nearby galaxies. It can explain the known population of ULXs with $M < 15M_{\odot}$ and bulk Lorentz factors for jets of $\gamma_{\rm j} \sim 5$. If this is true, the ULXs would be the stellar-mass analogues to blazars in the Universe.

1. Introduction

During the last years X-ray observations have revealed several ultra-luminous X-ray sources (ULXs) with luminosities $L_X \approx 10^{39} - 10^{40}$erg/s in nearby galaxies (e.g., La Parola et al. 2001; Mizuno, Kubota & Makishima 2001; Bauer et al. 2001). Some of the ULXs have shown spectral transitions from a soft spectrum to a hard power law and are highly variable (e.g., Mizuno & Kubota & Makishima 2001; Kubota et al. 2001), supporting the idea that they can be attributed to accreting objects. But for accretion powered objects the Eddington limit $L_{\rm Edd} \approx 1.25 \times 10^{38} \frac{M}{M_{\odot}}$erg s^{-1} generally applies, implying that ULXs are super-Eddington for stellar mass objects. Therefore, if the observed X-ray luminosities are created by isotropically radiating accretion disks, we need to postulate a population of intermediate-mass black holes of $50 - 500M_{\odot}$. As discussed in Kubota et al. (2001), however, the measured inner-disk temperatures of the ULXs ($T_{\rm in} = 1.0 - 1.8$keV) are too high for theses masses. Furthermore, there is no established formation scenario for such high mass black holes. These problems have already been discussed by King et al. (2001), where the authors propose anisotropic emission as an alternative, but this is difficult to achieve via disk models. Markoff, Falcke & Fender (2001a) suggested that the spectrum of some X-ray binaries could be explained by a coupled disk/jet model, where some of the X-ray emission is produced by synchrotron and inverse-Compton radiation in the jet. The jet emission would naturally be relativistically beamed. This follows the idea that there may be a unification scheme between AGN and XRBs, in which — once one has established the jet model and the geometry — one only has to scale the accretion rates. Thus in analogy to blazars one will expect a population of microblazars. These are microquasars with relativistically beamed jets pointed towards the observer (Mirabel & Rodriguez 1999), which leads to a high amplification of the jet emission (one candidate: V4641 Sgr see Orosz & Kuulkers 2001). Here, we will first present a population synthesis model for disk/jet emission (Körding et al. 2002) and then give possibilities for further tests of the model.

2. Simple jet/disk model

Black hole candidate XRBs can be found mostly in two distinct states: a high/soft state where the observed spectrum is soft and thermally-dominated and a low/hard state dominated by a non-thermal hard power law spectrum (e.g., Nowak 1995). These states seems to be determined mainly by the accretion rate. One scenario for the evolution of XRBs is that the inner part of the accretion disk consists of an optically thin, advection-dominated accretion flow (ADAF) extends up to a transition radius $r_{\rm t}$ where the accretion flow turns into a standard (Shakura & Sunyaev 1973) optically thick disk (e.g., Esin et al. 1997). The low/hard state appears to be accompanied by persistent radio jets with optically thick synchrotron emission extending up to the near-infrared and optical (Fender 2001). The jet could produce soft X-rays by synchrotron and inverse Compton emission in the low/hard and the high/soft state. (Markoff et al. 2001a , 2001b & 2002 in prep)

To create a simple population synthesis model, including beaming effects of the jet emission, we make the following assumptions:

- We only consider neutron stars of mass $1.4M_{\odot}$ and black holes within a mass range of 5-15 $M_{\odot}$. For simplicity, we use a mass distribution of black holes given by $\mathrm{d}N/\mathrm{d}M = \mathcal{V}(M)$ =const.
- The ratio of active black holes to active neutron stars ($L_{\rm X} > 5 \cdot 10^{36}$erg s^{-1}) has been fixed to 13 % (e.g., Tanaka & Lewin 1997).

- black hole XRBs as well as neutron star XRBs can only be in two distinct spectral states (low/hard and high/soft). In which state a given XRB is depends only on the accretion rate.
- The underlying driver of the emission is the accretion rate $\dot{M}$ (i.e., not the *luminosity* directly). The probability that a given XRB has the accretion rate $\dot{M}$ is given by $\mathcal{W}(\dot{M})$ which we assume as a power law ($\dot{M}^{\xi}$) with a cutoff representing the Eddington limit.
- The distribution of accretion rates and jet parameters is identical for neutron stars and black holes.
- The soft X-ray emission is produced by an isotropically radiating disk and a relativistically beamed jet with efficiencies as discussed below.

With these assumptions the most important point for our disk/jet model is the translation of the accretion rate into X-ray luminosity of the disk and the jet in each state. To simplify we assume a sharp transition between the two states, occurring at a critical accretion rate $\dot{M}_C$. In the high state the disk luminosity increases linearly with the accretion rate as expected for a standard accretion disk. Below $\dot{M}_C$, the disk luminosity increases with $\dot{M}^2$ as expected for optically thin ADAFs (Narayan & Yi 1995; for a constant α-parameter). Assuming that the jet power scales linearly with $\dot{M}$, the optically thick jet synchrotron emission will scale roughly as $L_{\rm x,jet} \propto \dot{M}^{1.4}$ (Falcke & Biermann 1995 & 1999).

At high accretion rates the jet models for XRBs are not yet well developed, so we will discuss the two possibilities that there is a jet in the high state or that it does not form at all (see Merloni & Fabian 2002). In the latter case we assume that the jet breaks down immediately at the critical accretion rate $\dot{M}_{\rm C}$. If there is X-ray emission from the jet the scaling ($L_{\rm x,jet} \propto \dot{M}^{1.4}$) must break down when a significant fraction of the jet power is radiated away. In this phase the radiated power can only increase linearly with jet power. This happens in the high state, roughly at $\dot{M} > \dot{M}_{\rm C}$, where the jet may be inverse-Compton cooled (radiating soft X-rays) by the accretion disk. However, since the jet for this state is not well understood, we simply fix the luminosity of the jet at $L_{\rm jet} = \eta L_{\rm disk}$ at $\dot{M}_C$, where η is a free parameter.

In summary, we use the following parameterization for the soft X-ray luminosity of accretion disk and jet:

$$
\begin{aligned}
L_{\rm disk} &= \begin{cases} \epsilon \left(\frac{\dot{M}}{\dot{M}_C}\right) \dot{M}c^2 & \text{if} \quad \dot{M} < \dot{M}_C \\ \epsilon \dot{M}c^2 \quad \text{if} \quad \dot{M}_C < \dot{M} < \dot{M}_{\rm Edd} \end{cases} \\
L_{\rm jet} &= \begin{cases} \eta\epsilon \left(\frac{\dot{M}}{\dot{M}_C}\right)^{0.4} \dot{M}c^2 & \text{if} \quad \dot{M} < \dot{M}_C \\ \eta\epsilon \dot{M}c^2 \quad \text{if} \quad \dot{M}_C < \dot{M} < \dot{M}_{\rm Edd} \ \text{or} \ 0 \end{cases}
\end{aligned}
\qquad (1)
$$

Where ϵ denotes the efficiency of the standard accretion disk which we set to $\epsilon = 0.1$ in the following discussion. For a given mass M the parameter $\dot{M}_{\rm Edd}$ has been chosen such that the luminosity of the disk and the jet integrated over all angles is equal to the Eddington luminosity of $1.25 \cdot 10^{38} \frac{M}{M_\odot}$erg s^{-1}.

While the disk emission is isotropic, the jet emission depends on the angle to the line of sight (if $\gamma_{\rm j} > 1$). The emission of a continuous jet is given by Lind & Blandford (1985). The Doppler factor is $\delta = \frac{1}{\gamma_{\rm j}(1-\beta\cos\Theta)}$. If the emission in the rest frame of the jet follows a power-law with spectral index α, the observed emission is proportional to $\delta^{2+\alpha}$. The probability of seeing an object with an emission exceeding L when in the rest frame the jet emits $L_{\rm loc}$ is:

$$
P(L, L_{\rm loc}) = \frac{1-\beta}{\beta} \left(\left(\frac{L_{\rm max}}{L} \right)^{\frac{1}{2+\alpha}} - 1 \right), \qquad (2)
$$

where $L_{\rm max} = \delta^{2+\alpha}(\Theta = 0) L_{\rm loc}$ is the maximal emission. To derive this we only consider the jet component pointing towards us and then integrate over randomly distributed inclination angles. Since we only discuss jets with $\gamma_{\rm j} > 2$, the emission of the counter-jet is largely negligible. In the high state the jet emits a factor η less radiation than the disk, but due to relativistic beaming the jet will dominate the radiation at small inclination angles. For example $\gamma_{\rm j} = 5$ will boost a fraction of 2% of the binaries by a factor of 77, more than making up for the lower efficiency of the jet.

The parameters $\dot{M}_C$ and η of a single population of XRBs at a given mass and accretion rate are well constrained by jet models:

- Critical accretion rate: $\dot{M}_C \sim 0.1 \dot{M}_{\rm Edd}$ (see Narayan & Yi 1995)
- Jet efficiency: $\eta \lesssim 0.3$ (see Falcke & Biermann 1995 & 1999)

The Lorentz factor for the jet is not that well constrained. While there are some reports of very low jet speeds others report higher lorentz factors around $\gamma_{\rm j} \approx 20$. Overall it seems that $\gamma_{\rm j} \simeq 2 - 5$ is consistent with the observations. For discussions see Mirabel & Rodriguez (1999), Fender et al. (1999), Gallo et al. (2002) in prep.

With this model and the parameters described above we are able to calculate the luminosity function. The emission in the rest frame of the jet and the disk is given by Eq. (1). This yields together with Eq. (2) for the estimated number of XRBs with a X-ray luminosity greater than L:

$$
\begin{aligned}
N(L) \; = \; & \sum_{i=N,B} \mathcal{N}_i \int dM \int d\dot{M} \mathcal{V}_i(M) \mathcal{W}_i(\dot{M}) \cdot \\
& P(L - L_{\rm disk}(\dot{M}), L_{\rm jet}(\dot{M}))
\end{aligned}
\qquad (3)
$$

where the sum runs over the two populations.

3. Data

A single galaxy has only marginal statistics in the high luminosity regime. To test our model we therefore used a combination of properly scaled Chandra data from the galaxies M101, M31 and M82 (Pence et al. 2001; Di Stefano et al. 2001; Griffiths et al. 2000) in the lower luminosity regime ($\leq 5 \cdot 10^{38}$erg/s) . These are three close

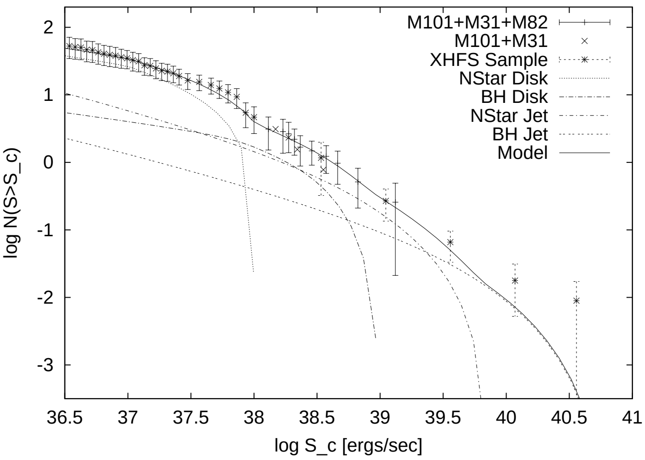

Fig. 1. Comparison of our model of the luminosity function with the data. The parameters are $\gamma_{\rm j} = 5$, $\eta = 0.3$, $\dot{M}_C = 0.1$, $\xi = 1.4$. Also shown are the individual contributions of the disk and the jet.

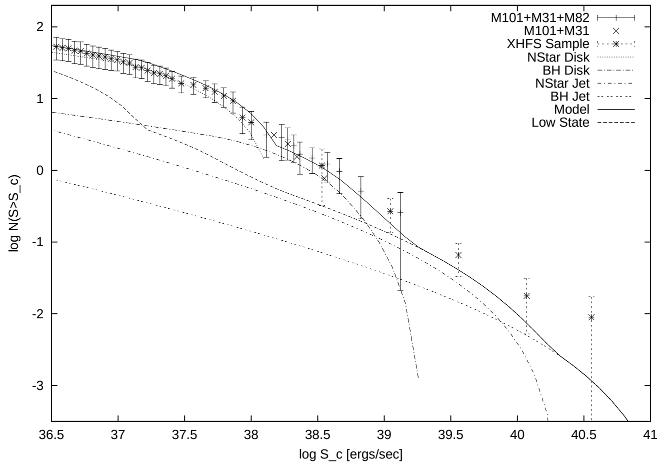

Fig. 2. Model without jet emission in the high state — Lorentz factor $\gamma_{\rm j} = 15$

($D < 10$ Mpc) galaxies with good Chandra data published. For the higher luminosities we used data of 49 spiral galaxies from the XHFS-sample by Roberts and Warwick (2000). To derive the higher luminosities the authors of the papers used an absorbed power law model with $N_H \approx 10^{21}/\mathrm{cm}^2$ and a photon index $\alpha \approx 1.7$, but the values are not always directly fitted, introducing a small additional error (≈ 10 %) in the luminosity estimate. As we are only interested in the slope of the luminosity function in a log$N$ - log S plot, these errors will not play an important role. We corrected the luminosities so that they all refer to the 2-8 keV band.

The overall scaling of the data is arbitrary, because the number of XRBs strongly depends on the history of star formation, but the slope of the luminosity function should be more general. As a reference galaxy we take M101, to which we scale the populations of the other galaxies in the overlapping luminosity regime. For the original data we use standard counting errors and normal error propagation. Because we are showing a cumulative distribution, the errors for each point are not independent.

4. Results

To compare our simple model with the data we evaluate the integral in Eq. (3) numerically. First we discuss the case that there is significant X-ray emission coming from the jet in the high state. The free parameter ξ and absolute normalization have been fitted to the data at $L_{\rm x} \leq 10^{37}$erg s^{-1}. We obtain a best-fit value of the accretion rate index $\xi = 1.4$. (note that the luminosity does not scales linearly in this regime).

Fig. 1 shows the result for our best-fit model with $\gamma_{\rm j} = 5$ and $\eta = 0.3$, together with the combined data set discussed above. In this plot we also show the individual contributions of the disks and jets from neutrons stars and black holes to the overall distribution. The Eddington limit clearly shows up as breaks at the respective luminosities but with $\gamma_{\rm j} = 5$ the beaming produces emission up to 10^{40}erg s^{-1}.

The high luminosity domain depends linearly on η while its dependence on $\gamma_{\rm j}$ goes as $\gamma_{\rm j}^{2.7}$, a slight decrease of $\gamma_{\rm j}$ can be compensated by an increase of η and vice versa. For $\gamma_{\rm j} = 5.8$ or $\gamma_{\rm j} = 7.5$ we can find $\eta = 0.2$ or $\eta = 0.1$, but the fit gets progressively worse at higher Lorentz factors. Reasonably demanding $\eta \lesssim 0.3$ for the radiative efficiency of the jet sets a lower limit for $\gamma_{\rm j} \gtrsim 5$. The model is stable for changes in the other parameters (critical accretion rate, power law indices of $L_{\rm disk}(\dot{M})$ and $L_{\rm jet}(\dot{M})$, black hole mass distribution).

The second possibility is that in the high state the jet is not forming at all. As the total power from the jet in its rest frame is at most $\eta \frac{\dot{M}_C}{\dot{M}_{\rm Edd}} L_{\rm Edd}$, beaming with Lorentz factors of $\gamma_{\rm j} = 5$ (yields a factor of $\sim 10^2$) can not explain the existence of ULXs. But with higher Lorentz-factors around $\gamma_j \approx 15$ the population can be reproduced, as shown in Fig. 2. The other parameters besides γ_j are chosen as before. In this figure we also show the contribution from the XRBs in low state. In this case the low state XRBs dominate the luminosity function at low luminosities (below $10^{36.5}$ erg/s) and at high luminosities again due to boosting.

It should be mentioned that the introduction of a population of intermediate-mass black holes could explain the population of ULXs as well as the jet/disk model. We tested that a population of black holes with masses of $20 - 1000 M_\odot$ distributed as a power law with index of roughly -2 can fit the luminosity function within the given errors.

5. Possible distinctions of the Models

The spectrum of an XRB in the low/hard state is characterized by a hard power law with possibly a black body component, while the high state has a softer spectrum. Unfortunately the shape of the spectrum of a beamed jet

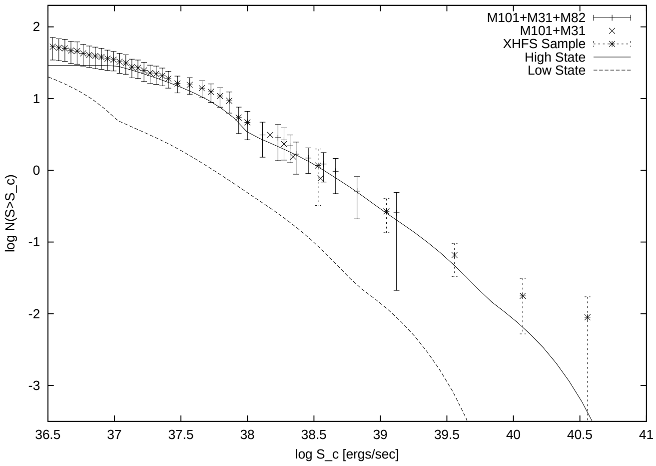

Fig. 3. Luminosity functions of XRB in the Low/Hard State and the High/Soft State.

in the high state is unknown. It could well be that it is peaked, and due to boosting we look flat part of it, resulting in a hard spectrum. Even if the distinction between the low and the high state is difficult, it is possible to make log N - log S plots for hard and soft spectra separately, giving a hint to the luminosity function of XRBs in the low and the high state. The prediction of the disk/jet model with emission from the jet in the high state is shown in Fig. 3 and could be compared with observations if sufficient data became available. The plot for the model with no jet in the high state can be found in Fig. 2.

A second possibility to check if non-thermal emission from jets plays a role for ULXs is to search for radio emission. Boosting a 10 mJy Galactic XRB with a Lorentz factor of $\gamma \sim 5$ (yields a factor of $\sim 10^2$) and placing it at $D \sim 3$ Mpc would yield only a faint 10 μJy source. Furthermore the emission of the accretion disk will quench the radio emission, reducing the flux even more and making radio detections difficult.

6. Summary and Discussion

To investigate whether beamed emission of jets could explain the existence of ULXs, we calculated the luminosity distribution of X-ray point sources using a coupled disk/jet model. We assumed that the emission of accretion disks is isotropic and scales as an ADAF below a critical accretion rate ($0.1\dot{M}_{\rm Edd}$), while scaling as a standard disk above. The soft X-ray emission from the jet is subject to relativistic beaming and scales with the accretion rate according to the jet models of Falcke & Biermann (1999) and Markoff et al. (2001a & 2001b) in the low state. For the high state we considered two cases. First that there is significant X-ray emission from the jet in the high state and second that the jet does not form at all.

The calculated luminosity functions are compared with a combined data set of three close galaxies and the XHFS sample. Within the statistical errors both models agree with the measured data and can fully account for the population of ULXs as well as the introduction of a new population of intermediate-mass black holes.

If one assumes the existence of a jet in the high state, it is necessary to have moderately high Lorentz factors around $\gamma \sim 5$ and fairly high jet efficiencies ($\eta = 0.1 - 0.3\%$) to fit the observed luminosity function. Otherwise, if the jet does not form in the high state, one needs very high Lorentz factors around $\gamma_{\rm j} \approx 15$ to create a sufficient amount of ULXs. Clearly, more intense modeling of jets in the high state and comparison to X-ray data is needed.

With the current statistics it is not possible to distinguish between the different models. But using log N - log S plots for the different spectral states, radio detections or variability it could be possible to give a final answer on the nature of ULXs.

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