Abstract. Galactic binary systems that contain a black hole candidate emit hard X-rays in their low luminosity mode. We show that this emission can be understood as due to the Compton scattering of photons from the companion star and/or the accretion disk by relativistic electrons in a jet. The same electrons are also responsible for the radio emission. Two sources — XTE J1118+480 and Cygnus X-1 — are modelled as representatives of black holes with low and high luminosity companion stars respectively. We further show that the ultraluminous compact X-ray sources observed in nearby galaxies have the properties expected of stellar mass black holes with high luminosity companions in which the jet is oriented close to our line of sight.

Key words: X-rays: binaries - stars: individual: Cygnus X-1, XTE J1118+480 - radiation mechanisms: non-thermal
External Compton emission from relativistic jets in Galactic black hole candidates and ultraluminous X-ray sources

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1. Introduction

Several Galactic black hole candidates in X-ray binary systems show evidence of relativistic outflows, and are collectively referred to as microquasars (Mirabel & Rodríguez 1999). These objects emit in two different X-ray states (Grove et al. 1998). In the high-soft state the spectral energy distribution peaks at a few keV, above which there is a soft power law component. In the low-hard state a hard power law extends to at least 100 keV (Grove et al. 1998). Both states have been modelled in detail using the comptonisation of accretion disk photons from a hot corona containing a hybrid plasma of thermal and nonthermal electrons — for a review see Poutanen (1998). However, despite good agreement with the observed X-ray spectra, the disk-corona models are unable to account for the tight temporal correlation between the low-hard X-ray state and the radio emission (Corbel et al. 2000).

Radio jets have been detected in several microquasars (Mirabel & Rodríguez 1999), including Cygnus X-1, in which a one-sided relativistic jet has recently been resolved in observations made during the low-hard X-ray state (Stirling et al. 2001). There is increasingly strong evidence that outflows — possibly relativistic ones — may be an generic feature of the low-hard state of microquasars (Fender & Kuulkers 2001a). It has been suggested some time ago (Hjellming & Johnston 1988) that the radio emission is synchrotron radiation from conical jets. Recently it has been proposed that the synchrotron emission might extend up to X-ray energies, either in the extended jet structure (Atoyan & Aharonian 1999) or close to the base of the jet (Markoff et al. 2001). Also, inverse Compton scattering by relativistic electrons in the jets has previously been proposed as a mechanism for the production of X-rays and gamma-rays (Band & Grindlay 1988, Levinson & Blandford 1990, Atoyan & Aharonian 1999).

In this letter we show that the low-hard state X-ray emission of microquasars can be understood as Compton scattering of photons from the companion star and/or the accretion disk (external Compton scattering or ECS) by relativistic electrons in the persistent jet. We apply this idea to two sources typical of systems with low and high mass companion stars, and show that the ultraluminous compact X-ray sources observed in nearby galaxies (Makishima et al. 2000) display the properties of beamed microquasars with high mass companion stars.

2. ECS in the low-hard state

In the low-hard X-ray state the relativistic electrons in the jet are exposed to the photon fields of the companion star and the accretion disk formed around the black hole, and therefore emit inverse Compton radiation predominantly by up-scattering these photons. The relative importance of the two seed photon sources depends primarily on their energy densities at the base of the jet, where energetic particles are injected. Whereas the luminosities of the star and disk are in principle observable, only upper limits to the size of the emitting region and its distance from the black hole can be set. Consequently, only lower limits on the energy densities can be estimated.

Consider now relativistic plasma injected at a jet inlet of radius \( R \). The plasma flows with a bulk Lorentz factor \( \Gamma \) and velocity \( \beta c \), where \( c \) is the speed of light. For simplicity, assume that, in the comoving frame, electrons are injected isotropically with a power-law distribution of index \( p \) confined between Lorentz factors \( \gamma_1 \) and \( \gamma_2 \). The environment is permeated by an isotropic monoenergetic photon field of photon energy \( \epsilon_0 \) in units of \( mc^2 \) and energy density \( U \). The plasma suffers inverse Compton losses until it has reached a distance \( l \) from the inlet at which the radiation field drops off significantly. The average time spent by electrons in this part of the jet — the escape time \( t_{esc} \) — is parameterised in units of the light crossing time \( t_{esc} = k l / c \), where \( k \approx 1 \). The photon energy density \( U \) is taken to be constant within the emission region. The comoving photon density in the blob frame can be written as \( U' \approx \Gamma^2 U \approx \Gamma^2 L_s / 4 \pi cd^2 \), where \( L_s \) is the luminosity of the dominant photon source and \( d \) is the distance of the emitting plasma from this source. Assuming that Com-
ton losses dominate, the Lorentz factor $\gamma_b$ at which the cooling and escape times are equal is

$$\gamma_b \approx \frac{3m_e c}{4\sigma_T \Omega'_{\text{esc}}} = \frac{3m_e c^3 d^2}{\sigma_T k L_{\gamma} \Gamma^2}$$

(1)

The spatially averaged electron energy distribution in the comoving frame can be approximately written as

$$n'(\gamma') = \begin{cases} \frac{Q k}{4\pi} \gamma'^{-p} & \text{if } \gamma_1 \leq \gamma' \leq \gamma_b \\ \frac{Q k \gamma_b}{4\pi} \gamma^{-(p+1)} & \text{if } \gamma_b \leq \gamma' \leq \gamma_2 \end{cases}$$

(2)

where $Q$ is a normalisation constant related to the relativistic electron power $P_{\text{inj}}$ injected in the jet by

$$P_{\text{inj}} = \frac{4\pi}{3} R^2 Q \Gamma^2 \beta m_e c^3 \frac{\gamma_2^{2-p} - \gamma_1^{2-p}}{2-p}.$$  

(3)

The spectral index of the external Compton spectrum increases from $(p - 1)/2$ to $p/2$ at the break energy $\epsilon_b = 4\epsilon_0 \gamma_b^2 D^2$, where $D = 1/\Gamma(1-\beta \cos \theta)$ is the Doppler factor and $\theta$ is the angle between the jet axis and the observer’s line of sight. For a continuous source, the spectral index of EoS for energies $\epsilon_b \leq \epsilon \leq \epsilon_{\text{max}}$, where $\epsilon_{\text{max}} = 4\epsilon_0 \gamma_b^2 D^2$, is (Georganopoulos et al. 2001)

$$\frac{d\epsilon}{d\Omega} \approx D^3 + \frac{Q k \gamma_b V \sigma_T e U_{\gamma}^2}{\pi \epsilon (2+p)(4+p)} \left( \frac{\epsilon}{\epsilon_0} \right)^{-p/2},$$

(4)

where $V = \pi R^2 l$ is the volume of the source. For $p < 2$ the luminosity per logarithmic energy interval at the peak energy $\epsilon_{\text{peak}} \approx \epsilon_0 D^2 \gamma_2^2$ of the spectral energy distribution given by $\epsilon \, d\epsilon / d\Omega$ scales as $D^5$,

$$L_{\text{peak}} = 4\pi \left( \frac{d\epsilon}{d\Omega} \right)_{\epsilon=\epsilon_{\text{peak}}} \approx \frac{3\pi m_e c^3 Q R^2 \gamma_2^{2-p} D^5}{(2+p)(4+p) \Gamma^2}.$$  

(5)

2.1. Microquasars with a low mass companion

We focus now on the low-hard X-ray state of microquasars with a low mass companion. These are typically systems with a star of K–M spectral type. The microquasar XTE J1118+480 is such a system, consisting of a black hole of mass $M \approx 6.5 M_{\odot}$ and a K7–M0V star of luminosity $L_{\ast} \approx 2 - 6 \times 10^{32} \text{ erg s}^{-1}$ separated by $R_{\ast} \approx 1.7 \times 10^{11} \text{ cm}$ (McClintock et al. 2001). The luminosity of the accretion disk during the active phase is $L_d \approx 8.6 \times 10^{35} \text{ erg s}^{-1}$, with a peak photon energy $\approx 24 \text{ eV}$ (McClintock et al. 2001). The accretion disk is much brighter than the companion star. Assuming that the emission site is located on the axis of the accretion disk, perpendicular to the orbital plane of the binary system, the photon energy density at the emission site is dominated by accretion disk photons.

The X-ray emission has a spectral index $\alpha \approx 0.8$ and a peak luminosity $L_{\text{peak}} \approx 4.3 \times 10^{35} \text{ erg s}^{-1}$ at an energy $\approx 100 \text{ keV}$. If this arises from ECS of accretion disk photons, the maximum energy electron is $\gamma_2 \approx (\epsilon_{\text{peak}}/\epsilon_0)^{1/2} \approx 65$ for a system in which beam is insignifying. Assuming that the observed spectral index $\alpha \approx 0.8$ is due to the cooled part of the electron distribution, the corresponding electron injection index is $p = 2\alpha = 1.6$.

In this source there is evidence for a compact jet (Fender at al. 2001) and, although its velocity in not determined, we assume, as discussed in the introduction, that it is mildly relativistic, adopting for illustration a bulk motion Lorentz factor $\Gamma = 2$ and a Doppler factor $\delta = 1$, which corresponds to an angle between the jet axis and the line of sight $\theta \approx 55^\circ$. To reproduce the observations we set $d = 10^8 \text{ cm}$, approximately the inner radius of the truncated accretion disk (Esin et al. 2001). The jet inlet is taken to be $R = d$, and we further set $l = 2d$. Figure 1 shows the spectral energy distribution, with injected electron power $P_{\text{inj}} = 0.05 L_{E}$, where $L_{E}$ is the Eddington luminosity of the black hole. The shaded area represents observations (McClintock et al. 2001). The solid line, corresponding to our ECS model, peaks at $\approx 100 \text{ keV}$, with a spectral index $\alpha = 0.8$.

2.2. Microquasars with a high mass companion

The prototype of this class is the source Cygnus X-1. This microquasar has a supergiant companion of spectral type O9.7 Iab, luminosity $L_{\ast} \approx 9.6 \times 10^{38} \text{ erg s}^{-1}$ and a photon energy $\approx 27 \text{ eV}$ (Herrero et al. 1995). The separation between the companion star and the massive black hole (M...
\[\gamma_2 \approx \left(\frac{\epsilon_{\text{peak}}}{\epsilon_0}\right)^{1/2} \approx 165.\]

In Fig. 3, we plot the model spectral energy distribution for the above parameters. The two solid lines correspond to the ECS emission due to the companion star (1) and accretion disk (2) seed photons for \(\theta = 50^\circ\) (\(\delta = 1.12\)). Since our model has an abrupt cutoff of the electron energy distribution at \(\gamma_2\) it gives a poor fit to the very soft emission between 100 KeV and 1 MeV. Note, however, that the \(\sim 3\) MeV emission arises naturally as the ECS of accretion seed disk photons.

### 2.3. Ultraluminous X-ray sources

Variable and, therefore, compact X-ray sources of luminosity up to \(\sim 10^{41}\) erg s\(^{-1}\) have been observed in nearby galaxies (Makishima et al. 2000). These sources are displaced from the galactic centre and, if they radiate isotropically, indicate a black hole mass \(M \geq 50 - 100 M_\odot\). However, it is difficult to understand how such systems could be formed in the required number, which has led King et al. (2001) to the conclusion that the emission may, in fact, be beamed. This immediately suggests a connection with the model presented above for Cygnus X-1, of nonthermal ECS from a relativistic jet. In the context of a synchrotron model, a similar idea has been taken up independently by Koerding et al. (2001).

In the ECS model, the peak luminosity appears amplified due to Doppler boosting by a factor of \(D^5\) for a continuous jet. Even using the mildly relativistic jet parameters appropriate for Cygnus X-1 (\(\Gamma = 2, D_{\text{max}} = 4\)) leads to a substantial maximum amplification factor of approximately 1000. Such a source could reach an apparent luminosity \(\sim 2 \times 10^{46}\) erg s\(^{-1}\). To illustrate this point, we plot in Fig. 3 the spectral energy distribution predicted for an observer at an angle \(\theta = 10^\circ\) to the jet. Note that the beaming of the component due to accretion disk photons is weaker by a factor of \((1 - \beta \cos \theta)^{p/2}\) (Dermer et al. 1992).

The idea that ultraluminous X-ray sources are related to microquasars such as Cygnus X-1, is compatible with recent observations. Ultraluminous sources have exhibited transitions from a highsoft to a low-hard state and vice-versa, similar to the spectral transitions of Galactic microquasars (Kubota et al. 2001; La Parola et al. 2001). Also, optical observations suggest that the ultraluminous source NGC 5201 X-1 may have an O star companion (Roberts et al. 2001). Finally, a possible X-ray periodicity has been observed in a ultraluminous source in the spiral galaxy IC 342 (Sugihara et al. 2001), which, if interpreted as orbital modulation, is compatible with emission from a microquasar with a high mass companion star.

### 3. Discussion and conclusions

We show that the X-ray emission in the low-hard state of microquasars can be understood as ECS radiation from electrons in a relativistic jet. These electrons are also responsible for the radio emission occurring further down-
stream in the jet. Depending on the type of binary system, the ECS seed photons originate either from the companion star and/or from the accretion disk. In our model we assume that ECS losses dominate at the base of the jet. This requires that the magnetic field energy density in the jet is lower than the external photon field energy density as seen in the frame comoving with the flow. In the case of XTE J118+480 this corresponds to \( B \lesssim 10^5 \) G whereas for Cygnus X-1 \( B \lesssim 100 \) G. These upper limits are compatible with standard accretion disk magnetic fields, assuming magnetic flux conservation between the accretion disk and the jet (Sams et al. 1996). In our model the jet is optically thick to synchrotron radiation up to \( \sim \) far IR energies; it becomes optically thin at \( \sim \) IR energies and the synchrotron emission cuts off at \( \sim \) UV. Thus, the external optical and UV photons are able to penetrate the jet and act as seed photons in the ECS mechanism. Depending on the Thomson thickness of the outflow, a weak comptonisation tail due to multiple scatterings may be formed up to energies \( \gamma mc^2 \).

We have also demonstrated that the low-hard state of a Galactic microquasar can appear as an ultraluminous X-ray source, if viewed under a suitable angle. Our discussion of these sources focused on the low-hard state only. However, by implication the soft X-ray state must also be beamed, so that the relativistic jet must still exists in the high-soft state. In our model, ECS dominates the energy losses, so that it is natural to assume that the increased accretion disk luminosity in the high-soft state quenches the nonthermal electrons, thereby simultaneously producing the X-ray emission and suppressing the radio jet.

To summarise, we present a model in which the X-ray emission of microquasars in the hard state is due to external Compton scattering by the energetic electrons in a relativistic jet, the same electrons being also responsible for the radio emission. The seed photons are stem from the companion star and/or the accretion disk. We show that this model can explain the ultraluminous X-ray sources observed in nearby galaxies as beamed microquasars similar to Cygnus X-1.

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