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Gamma-ray emission from jets in galactic microquasars

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Abstract. Strong evidence exists for the presence of powerful jets in the Low/Hard state of black hole candidate X-ray binaries, earning them the additional nomenclature "microquasars". In several of these sources, jets have been directly imaged, but all sources in the Low/Hard state show the flat-to-inverted radio spectrum which is the characteristic signature of optically thick synchrotron jet emission. This optically thick component can extend into the IR/optical, beyond which is a turnover to an optically thin regime. If indeed shock acceleration is present in the jet, as indicated by observations during flaring, this would account for the optically-thin power-law detected at higher frequencies. The high-energy cutoff of this power-law is determined by balancing cooling losses against acceleration, and could likely venture into the X-ray range. The same synchrotron-radiating energetic particles in the jet will also Compton upscatter external disk photons, as well as the synchrotron emission itself, resulting in a component that has the potential to extend into the γ-ray range. This is parallel to what is inferred from AGN, and thus these relatively nearby sources may serve as useful analogs for the study of cosmic ray acceleration and radiative processes in AGN, particularly in the limit of extreme cooling. We discuss the characteristics and detectability of this γ-ray emission, as well as a possible annihilation feature associated with jets impinging on dense gas, in the context of Galactic microquasars.

1 Introduction

Observations are providing increasing evidence that black hole candidate (BHC) X-ray binaries (XRBs) produce powerful collimated outflows when in the Low/Hard X-ray state (LHS). This state is characterized by a nonthermal power-law in the X-ray band and little, if any, thermal disk contribution (e.g., Nowak, 1995; Poutanen, 1998). Several Galactic systems in the LHS have directly resolved radio jets on scales from AU to parsecs. However, XRB jets also reveal themselves in the broadband LHS spectra with a flat-to-inverted radio synchrotron spectrum, analogous to the signature emission of jets in compact radio cores of AGN (Blandford & Königl , 1979; Hjellming & Johnston , 1988). This optically thick synchrotron emission continues up to at least the IR in some sources. For more background on the spatial, spectral and temporal evidence for powerful jets from LHS XRBs, see Fender (2001).

We know that jets play a significant role in the emission of Active Galactic Nuclei (AGN), even dominating the spectrum from radio through TeV γ-rays in the case of BL Lacs, with emission from optically thin synchrotron up to even 100 keV and higher (e.g. Pian et al. , 1998). By analogy, if the flat, optically thick synchrotron spectrum in XRBs, commonly attributed to jets, indeed extends into the IR and optical regimes, one would expect a corresponding optically thin power-law from shock acceleration at even higher frequencies. Shock acceleration is likely to be present in XRBs, given that optically thin power-law spectra are observed during their radio outbursts (e.g., Fender & Kuulkers, 2001, and refs. therein).

Nevertheless, most models for the broadband (X-ray) spectra of BHC XRBs focus only on the contribution of thermal disk plus inverse Compton (IC) emission from a hypothesized hot corona above the cooler disk (for a review see Poutanen, 1998). Any contribution from the jets is ignored despite the fact that they are known to contribute in the X-rays via synchrotron in AGN, and the fact that they are the only part of the system actually imaged.

For XRBs in the LHS, however, the evidence is mounting that there is, in fact, an intimate relationship between the radio and the X-rays. In at least two sources (GX 339-4 and Cyg X-1) there is an approximately log-linear relationship between the hard X-ray flux (dominated by the non-thermal power-law) and the radio emission (Brocksopp et al. , 1999; Corbel et al. , 2000), which in the case of GX 339-4 holds over 3 orders of magnitude of X-ray flux. Furthermore, for

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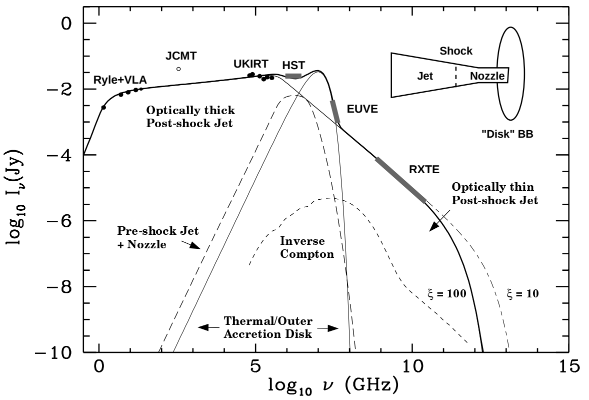

Fig. 1. XTE J1118+480 model fit to data, see Markoff et al. (2001) for data references and details. Synchrotron from the jets can account for almost the entire spectrum, similar to a nonthermally dominated AGN.

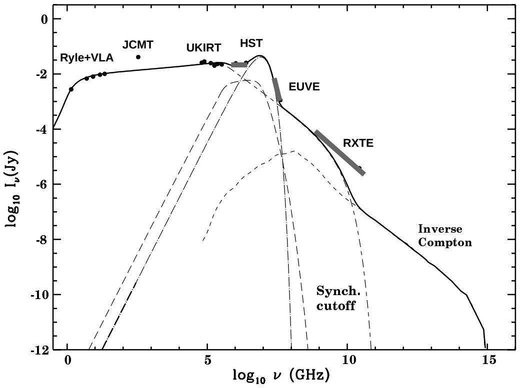

Fig. 2. Same as Fig. 1, with the acceleration cutoff and inverse Compton calculated for an increased number of of photons at the base of the jet. This would be expected if the inner disk radius decreased down to the last stable orbit, as is suggested to account for the High State of XRBs. We do not show this corresponding thermal spectrum here. The IC from the jet becomes observable for this higher photon field, giving the "Camel Back" shape in the power vs. energy spectrum. This also shows how the LHS hard power-law is destroyed in the process of change to the High State.

this same source, the radio and hard X-rays are simultaneously "quenched" by a factor of 30 when the softer X-rays attributed to the disk emission flare up. As soon as the soft X-rays die down, the hard X-rays and radio jump simultaneously back up again (Fender et al. , 1999). These data show an extreme coupling that is hard to explain, if the hard X-rays are not coming from the same source as the radio, i.e. the jet.

If the jets contribute via synchrotron to the X-rays, this raises the possibility of a jet contribution via IC at even higher frequencies, in analogy to BL Lacs. This would especially hold true during state changes where the seed photons from the disk become more numerous. We already know some microquasars such as 1E 1740.7-2942 are γ-ray emitters, but this would suggest that there are many more fainter emitters out there, contributing to the overall background. This also holds out promise that these relatively nearby Galactic sources can be studied in order to understand the physical processes occurring in their more distant cousins, AGN.

In the following sections, we describe a model for jet emission in the LHS of XRBs, and discuss the possible contribution in the γ-rays from the jet. We discuss both direct emission, and annihilation which could result upon impact of the jet on the ISM or clouds.

Gamma-rays produced in the jet

For our model (see Markoff, Falcke & Fender, 2001 for details), we start with a Blandford & Königl (1979) jet, modified to be part of a symbiotic system to include the accretion flow, which then determines the mass and energy input into the jet and which are conserved quantities. The geometry is no longer perfectly conical, but rather has a nozzle where the jet is accelerated before undergoing adiabatic expansion. One final modification is the consideration of a velocity gradient along the flow, due to work done during the jet expansion. Once the relationship between the jet and the accretion flow is fixed, all physical quantities in the jet are determined via the Euler equation, and conservation laws (Falcke & Biermann , 1995)

As an example, we use the recently discovered XRB XTE J1118+480 (Remillard et al. , 2000), which has been observed in the radio through X-rays (see Hynes et al. , 2000; Fender et al. , 2001; McClintock et al. , 2001, and refs. therein), and is also at sufficiently high Galactic latitude to allow the first ever EUV detections of an X-ray transient. The system is a BHC in the LHS, and although jets were not directly resolved with MERLIN to a limit of $< 65(d/\mathrm{kpc})$ AU (at 5 GHz; F01), its radio emission shows the flat characteristic jet spectrum.

We consider that an accretion disk is responsible for the optical-EUVE emission (Hynes et al. , 2000; Garcia et al. , 2000). One commonly invoked physical explanation for the LHS is that a standard thin, optically thick disk (Shakura & Sunyaev , 1973) exists only down to some transition radius $r_{\mathrm{tr}} \sim 10^2 - 10^3 r_{\mathrm{s}}$, ($r_{\mathrm{s}} = 2GM_{\mathrm{bh}}/c^2$), where the flow becomes hot and non-radiative (e.g., Esin et al. , 2001).

In AGN jets the high frequency, optically thin power-laws are taken to be the result of synchrotron emission from particles shock accelerated along the jet (e.g., Marscher & Gear, 1985). In such a case the crucial parameter for the high energy emission is the location z_{acc} of the first particle acceleration region in the jet. We assume the same process is occurring in the XRB jets, which explains the observed optically thin power-law. When the accreting plasma, assumed to be injected at the base of the jet with a Maxwellian distribution, then reaches the shock region, the standard diffusive shock acceleration process redistributes the particles into a power-law, starting roughly at the peak of the Maxwellian.

The spectral index of the particle energy distribution is $p \simeq 2-3$, typically found in the optically thin synchrotron emission of both AGN and X-ray binaries. For the case of XTE J1118+480, the unbroken X-ray power-law (see Fig. 1), implies $p \simeq 2.6$ for $E > E_{\mathrm{b}}$, which suggests some spectral steepening due to a cooling break. The acceleration ceases when the particles reach the energy $E_{\mathrm{e,max}} = \gamma_{e,max} m_{\mathrm{e}} c^2$ where the cooling/loss rates equal that of acceleration. These rates are dependent both on the energy of the particle, as well as the local physical parameters.

We account for energy losses at the shock via adiabatic losses, particle escape, IC and synchrotron. In our model for the LHS, due to the weak disk, synchrotron cooling dominates. For this case, when one sets the standard shock acceleration rate equal to the rate of cooling losses due to synchrotron, one finds a simple analytic expression for the maximum energy $\gamma_{\mathrm{e,max}} \propto (\xi B)^{-0.5} \left(\frac{u_{\mathrm{sh}}}{c}\right)$, where $\xi < c\beta_e/u_{\mathrm{sh}}$ (Jokipii , 1987) is the ratio between the diffusive scattering mean free path and the gyroradius of the particle, and has a lower limit at $\xi = 1$. The maximum synchrotron frequency is then

$$\nu_{\max} \propto \nu_{\mathrm{c}} \propto \xi^{-1} \left(\frac{u_{\mathrm{sh}}}{c}\right)^2 \quad \mathrm{Hz}, \tag{1}$$

where $\nu_{\mathrm{c}} \simeq \frac{3}{4\pi}\gamma^2_{\mathrm{e,max}}(eB)/(m_{\mathrm{e}}c)$ is the critical synchrotron frequency. This maximum corresponds approximately to the rollover of the power-law cutoff, and for $\xi = 100$ and $u_{\mathrm{sh}} \sim \beta_{\mathrm{s}} c$, we find a cutoff of ~ 80 keV. This cutoff is not dependent on the magnetic field, the jet power, or the shock location as long as we are in the synchrotron cooling dominated regime. Because we would expect XRBs to have similar shock structures, once ξ is roughly fixed observationally—thus determining the scattering between magnetic irregularities in the diffusive shock process—we should get similar cutoffs for different sources and accretion rates. This accounts for the "canonical" 100 keV cutoff seen in LHS spectra. This also shows that if synchrotron is the dominant cooling factor, the scattering ratio ξ must be small and/or the shock speed must be very large in order to get synchrotron into the γ-ray range. What is more likely is that a contribution comes from IC scattering, especially in the case of the disk flaring up.

The model fit to the data is shown in Fig. 1 for the parameters in the caption (and see Markoff et al. , 2001). The jet can account for almost the entire spectrum from radio to X-rays via synchrotron, using only $\sim 1\%$ of the total accretion power $\dot{M}c^2$. We show also how the synchrotron cutoff is dependent on the ratio ξ. For $\xi \sim 10$, the spectrum does not begin to turn over until the MeV range. If this were the case, the jet would be observable by *INTEGRAL* up to a few MeV. In this model, the IC contribution only begins to dominate over the synchrotron at 10^{12} GHz, or ~ 4 MeV with a flux that is currently below the sensitivity of today's observatories.

As mentioned above, the current limit on γ_e comes from synchrotron losses, as compared to external Compton such as in BL Lacs. For a much stronger external photon density, e.g., if the optically thick disk extends much closer in or is much more luminous such as would occur during the High State, this maximum energy could be further reduced due to IC losses, and the IC component would increase respectively. We show this in Fig. 2 for comparison, using the same data set as Fig. 1 for scale. In reality, this data set is not relevant because is was taken during the LHS. The thermal disk component would be much greater, the jet radio points would be quenched along with the hard X-rays as seen in Fig. 3. This erosion of the X-ray power-law due to Compton cooling qualitatively explains how the hard spectrum of the LHS disappears during the change to the Highs State. Fig. 3 also illustrates how the IC flux could go up to the observable range for missions such as *INTEGRAL* and *Whipple*, with the caveat that we the spectral index may also steepen, reducing visibility to the lowest γ-ray frequencies. The νL_ν spectrum would also show the classical "Camel Back" shape seen in BL Lacs.

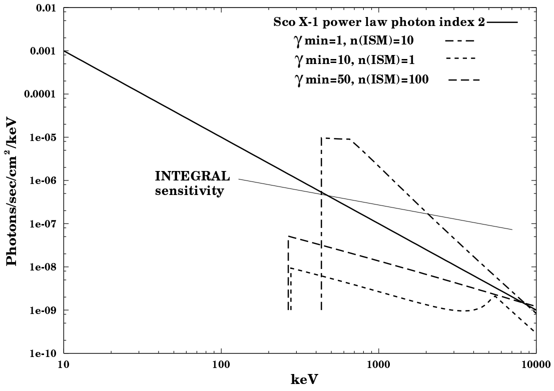

Fig. 3. Illustration of the possible contribution of annihilation radiation caused by the jet-ISM interaction for the case of XRB Sco X-1. Under certain circumstances the annihilation radiation could produce a quasi-persistent excess, visible to *INTEGRAL* at energies ≥ 400 keV (see text for details).

2 Gamma-rays produced via annihilation

Another physically distinct site for the production of hard X-rays and γ-rays would be the zone of impact of the jet onto dense regions of the local interstellar medium (ISM). This would only hold true if XRB jets are composed significantly of $e^{\pm}$ pairs. In this case the annihilation spectrum can be calculated arising from the continued action of the positrons in the jets acting upon the electrons in the cold ISM.

The total luminosity of the annihilation will be

$$L_{\mathrm{ann}} = n_{\mathrm{T}} V \int dE_\gamma \int d\gamma_{\mathrm{e}} \gamma_{\mathrm{e}} m_{\mathrm{e}} c^2 N_{\mathrm{e}}(\gamma_{\mathrm{e}}) \bar{v} \frac{d\bar{\sigma}}{dE_\gamma}, \tag{2}$$

following largely the notation of (Svensson , 1982), where n_{T} is the target density of cold electrons, in for example the interstellar medium (ISM) of a galaxy, or in a molecular cloud, V is the volume of the annihilation region, and the relativistic pair distribution is integrated over the annihilation cross section as well as the emitted spectrum.

If the timescale for annihilation is much longer than the life-time of the source then the entire population of deposited pairs will contribute to the observable annihilation flux. This implies that the pairs have not diffused out of the target gas, and likely the beam of the telescope, which is always the case for the parameters discussed here. For a power-law of pairs expected in a jet, $L_{\rm ann}$ will be dominated by the lowest energy pairs, and the cross-section will be approximately constant at $\sigma_{\rm ann} = 3/8\sigma_{\rm Th}$, where $\sigma_{\rm Th}$ is the Thomson cross-section.

Under this assumption, the integrated energy density of the particles from the jet colliding with the gas in the target volume is equal to some fraction η of the total jet luminosity $L_{\rm j}$. One can then express Eq. (2) as:

$$\begin{aligned} L_{\rm ann} &= \tau_{e^\pm}\eta L_{\rm j} \\ &= \frac{3n_{\rm T}}{8\gamma_{\rm e,min}}\eta L_{\rm j}T_{\rm j}(2-p)(1-p)c\sigma_{\rm Th}\ \ {\rm erg\,cm^{-3}}, \end{aligned} \qquad (3)$$

where p is the index of the pair distribution $N_{\rm e}(\gamma_{\rm e}) \propto \gamma_{\rm e}^{-p}$, $\gamma_{\rm e,min}$ is the minimum energy of the distribution, and $T_{\rm j}$ is the lifetime of the jet interaction with the target gas.

For a power law index $p > 2$, the ”optical depth” for pair annihilation is roughly $\tau_{\rm e^\pm} = 0.375 n_{\rm T} c(2-p)(1-p)T_{\rm j}\sigma_{\rm Th} \ll 1$. For $\tau_{\rm e^\pm} \approx 1$ we can express this as:

$$L_{\rm ann} = \eta L_{\rm j}. \qquad (4)$$

The requirements for a strong annihilation signal are then: high target densities, long source life-times and large jet powers. Clearly the annihilation radiation cannot be higher than a certain (possibly significant) fraction of the jet power.

In Fig. 2 we plot some possible emission spectra arising from the action of the jet in the bright XRB Sco X-1 on the ISM over a period of its estimated lifetime of 10^6 yr. It is clear that under certain conditions, this contribution from annihilation can dominate over the power-law extrapolated from lower energies. The annihilation spectrum is much broader than a line, but could still be identified with a mission such as *INTEGRAL*. Because of the relatively high predicted fluxes for low $\gamma_{\rm e,min}$, a non-detection could put constraints on $\gamma_{\rm e,min}$ for a pair jet, requiring that it be significantly higher than unity. Some effects might also work in our favor. Should the bulk of pairs not be in a power-law but in a Maxwellian at low energies, the chance of an annihilation feature would increase drastically.

Conclusion

The evidence from several Galactic XRBs in the LHS indicates that synchrotron from the jets could be contributing at least up to the X-rays, possibly even into the γ-ray range similar to some classes of AGN. This holds only in the case of a weak disk luminosity, because it is dependent on acceleration limited by synchrotron losses. We have illustrated how in the case of XTE J1118+480, the jet synchrotron can account for almost the entire spectrum of the source, suggesting that some XRBs may be nonthermally dominated. If seed photon field increases as during the change to the High State, there could be a window before the jet is quenched by cooling, in which the IC component is itself observable by today and future missions. The jet may also reveal itself via the annihilation of its positrons within the ISM or a molecular cloud, a signal which could be observable by *INTEGRAL* if the lifetime and power of the jet is high enough.

These results also suggest that we can increase our understanding of the physics of AGN disk/jet systems by studying even nearby sources. Observations in the X-rays and γ-rays reveal the highest energy physical processes, and could help us understand what is happening with the jet close to the event horizon. By modeling the action of the jet, and understanding the interplay of its contribution via synchrotron and IC to the overall spectrum, particularly during active disk states, we can hope to grasp the radiative processes in disk/jet systems at even galactic nucleus scales.

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