

Synchrotron outbursts in Galactic and extragalactic jets, any difference?

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Abstract. We discuss differences and similarities between jets powered by super-massive black holes in quasars and by stellar-mass black holes in microquasars. The comparison is based on multi-wavelength radio-to-infrared observations of the two active galactic nuclei 3C 273 and 3C 279, as well as the two galactic binaries GRS 1915+105 and Cyg X-3. The physical properties of the jet are derived by fitting the parameters of a shock-in-jet model simultaneously to all available observations. We show that the variable jet emission of galactic sources is, at least during some epochs, very similar to that of extragalactic jets. As for quasars, their observed variability pattern can be well reproduced by the emission of a series of self-similar shock waves propagating down the jet and producing synchrotron outbursts. This suggests that the physical properties of relativistic jets is independent of the mass of the black hole.

Keywords. Radiation mechanisms: nonthermal – shock waves – stars: individual (GRS 1915+105, Cyg X-3) – galaxies: active – galaxies: jets – quasars: individual (3C 273, 3C 279)

1. Introduction

Quasars and microquasars – their galactic analogs – are relativistic jet sources thought to be powered by super-massive and stellar-mass black holes, respectively (see Mirabel & Rodríguez 1998 for a review). Although the radio emission of microquasars tends to show a greater variety of behaviours, during some activity periods their radio variability pattern resembles that of quasars, but on much shorter timescales (hours or days instead of years). It is now rather well established for quasars that outbursts identified in their radio lightcurves are related to moving structures in the jet imaged with radio interferometric techniques. There is also growing evidence that these structures emitting synchrotron radiation are propagating shock waves along the jet flow rather than discrete ejected plasma clouds (Kaiser *et al.* 2000; Türlér *et al.* 2004).

Based on these facts, a natural step forward is to confront theoretical predictions of shock wave models with the observed evolution of the outbursts. The approach we developed since several years is to try to fit a series of self-similar model outbursts to the multi-wavelength monitoring observations of some of the best studied objects. Until now, we studied data sets of four objects: the quasar 3C 273 (Türlér *et al.* 1999; 2000), the blazar 3C 279 (Lindfors *et al.* 2006) and the microquasars GRS 1915+105 (Türlér *et al.* 2004) and Cyg X-3 (Lindfors *et al.* in prep.). In this short contribution, we try to compare and discuss the jet properties derived for these four sources as one of the first attempts to sketch out a more global picture of black hole jets across the range of mass.

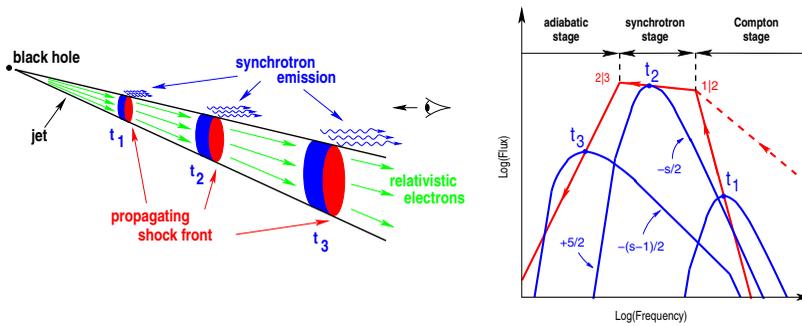


Figure 1. Schematic view of a propagating shock wave in a relativistic jet and the three-stage evolution of the associated synchrotron outburst according to the model of Marscher & Gear (1985) and with the modification proposed by Björnsson & Aslaksen (2000) (dashed line).

2. Data and Method

A description of the data sets and the method can be found in our previous publications listed above. We just recall here that for 3C 279 and 3C 273 we use data spanning one and two decades, respectively, whereas for GRS 1915+105 we use the data of 15 May 1997 in the plateau/state C/class χ state (Mirabel & Rodríguez 1998) and for Cyg X-3 the outbursts of Feb.–Mar. 1994 (Fender *et al.* 1997). The main change with respect to previous studies is that we use here consistently for all sources the modification proposed by Björnsson & Aslaksen (2000) for the initial Compton stage of the Marscher & Gear (1985) shock model in the case of only first-order Compton cooling. This flattens the initial rise of the spectral turnover with decreasing frequency, as shown schematically in Fig. 1. In the case of 3C 273 the jet parameters are such that this modification made the Compton stage completely flat or even inverted (decreasing turnover flux with time), which would make the model incompatible with infrared data. This problem could however be solved by assuming that the shocked material is viewed sideways (Marscher *et al.* 1992). Such an assumption is not unreasonable in sources with highly superluminal jets, as the jet angle θ to the line of sight for this to happen is defined by $\cos(\theta) = \beta \Leftrightarrow \sin(\theta) = 1/\gamma$, which is the same condition that maximizes the apparent transverse velocity β_{app} for a given bulk velocity $\beta = v/c$. We therefore use here a sideways orientation of the jet for both extragalactic sources and a face-on orientation for both microquasars.

3. Results and Discussion

Due to lack of space we cannot present here the derived evolution of the average outburst in the four sources. The main differences we obtain with the changes to the model described above, is that in general we do not obtain an almost flat synchrotron stage, but one with a much steeper increase of flux with turnover frequency, which becomes more difficult to distinguish from the now shallower Compton stage. There is therefore some uncertainty whether the synchrotron stage exists at all or whether there is a direct transition from the Compton to the adiabatic stage. Another interesting point is that for the initial phases of the outburst evolution we suspect the spectral turnover ν_m not to be due to synchrotron self-absorption as assumed, but to a low energy cut-off of the electron energy distribution. Evidence for this is the shallow spectral slope we find below the turnover frequency and which we describe in our modelling by an inhomogeneous synchrotron source. However, one would rather expect the source to become more inhomogeneous with time as the source increases in size, whereas we observe the

Table 1. Physical jet properties of the four objects derived for the average model outburst at the time when it reaches a maximum flux (i.e. around the transition to the final decay stage).

Object	M_{BH} [M_{\odot}]	Δt_{obs} [s]	Δl [AU]	θ_{src} [mas]	B [G]	K [$\text{erg}^{\text{s}^{-1}}/\text{cm}^3$]	s	u_e [erg/cm^3]	u_B/u_e
3C 273 ¹	$6.6 \cdot 10^9$	$3.1 \cdot 10^7$	$3.1 \cdot 10^6$	0.39	0.13	$6.7 \cdot 10^{-7}$	2.52	$1.3 \cdot 10^{-4}$	5.6
3C 279 ²	$3 \cdot 10^8$	$3.1 \cdot 10^7$	$4.7 \cdot 10^6$	0.25	0.26	$8.5 \cdot 10^{-7}$	2.09	$1.4 \cdot 10^{-5}$	195
Cyg X-3 ³	< 3.6	$8.6 \cdot 10^4$	$6.6 \cdot 10^2$	4.6	0.83	$1.9 \cdot 10^{-4}$	1.68	$7.9 \cdot 10^{-5}$	344
GRS 1915 ⁴	14	$1.8 \cdot 10^3$	3.1	0.02	0.15	$6.7 \cdot 10^2$	1.79	$1.4 \cdot 10^3$	$6.3 \cdot 10^{-7}$
GRS 1915 ⁵	14	$1.8 \cdot 10^3$	6.7	0.07	7.5	$3.4 \cdot 10^{-1}$	1.79	$4.7 \cdot 10^{-1}$	4.8

¹ M_{BH} from Paltani & Türler (2005) and with $\beta_{\text{app}} = 10$ & $\theta = 10^\circ$ (Savolainen *et al.* 2006).

² M_{BH} from Wang *et al.* (2004) and with $\beta_{\text{app}} = 10$ (Jorstad *et al.* 2004) & $\theta = 5^\circ$ (see text).

³ M_{BH} from Stark & Saia (2003) and $\beta = 0.81$, $\theta = 14^\circ$ & $d = 10$ kpc (Mioduszewski *et al.* 2001).

⁴ M_{BH} from Greiner *et al.* (2001) and $\beta = 0.6$, $\theta = 61^\circ$ & $d = 9$ kpc (Türler *et al.* 2004).

⁵ alternative with $\beta = 0.9$, $\theta = 55^\circ$ & $d = 7$ kpc (uncertainty on d , see Fender *et al.* 2003).

opposite behaviour. An alternative explanation is that this flatter spectral index mimics the characteristic $\nu^{1/3}$ slope expected when self-absorption becomes important at a lower frequency than the synchrotron frequency associated to the electrons with minimal energy (see e.g. the spectral shape in the upper panel of Fig. 1 of Granot & Sari 2002). This interpretation could also explain the too rapid evolution of the turnover frequency with time that we observe in both galactic sources. Currently, this is described in our modelling by a non-conical jet with an opening angle increasing with time, but the physical justification for such a trumpet-like shape is not clear.

More quantitatively, we made a first attempt to derive the physical properties of the jets, which we summarize in Table 1. These values have been derived for the particular point when the synchrotron spectrum of the average outburst reaches its maximum flux, which happens here for all sources at the transition to the final adiabatic cooling phase. A critical parameter is the angular size θ_{src} of the source of synchrotron emission, which we assume to be equal to the width of the jet. By assuming a same jet opening half-angle of 2° for all sources, θ_{src} can thus be calculated from the length along the jet Δl traveled by the shock during the observed time interval Δt_{obs} needed for the outburst to reach a maximal flux. This length itself depends on good estimates of the object's distance d , the jet angle θ to the line of sight, and the apparent $\beta_{\text{app}} = v_{\text{app}}/c$ or real $\beta = v/c$ jet speed. We can then simply use Eqs. (3) to (5) of Marscher (1987) to calculate the magnetic field strength B , the normalization K of the electron energy distribution $N(E) = K E^{-s}$ and the energy density u_e of relativistic electrons. For the latter we use a ratio ν_2/ν_1 of 10^4 between the highest ν_2 and the lowest ν_1 frequency considered for integration. Although these formula apply strictly to a homogeneous and spherical synchrotron source, we do not expect the emitting material in the jet to depart a lot from this ideal case at the start of the final decay stage. Finally, we calculate the energy density of the magnetic field $u_B = B^2/(8\pi)$ and the ratio u_B/u_e , which is extremely sensitive to the source size as: $u_B/u_e \propto \theta_{\text{src}}^{17}$. It is thus quite surprising to get values close to equipartition (i.e. $u_B \approx u_e$) for all objects when assuming a same jet opening half-angle of 2° and realistic values for the jet orientation and speed as given in the footnotes of Table 1. For GRS 1915+105 there is an important uncertainty on the distance d and jet velocity β (Fender *et al.* 2003) and actually we find that higher jet speeds and smaller distances favor equipartition. For 3C 279 we note that taking a viewing angle θ of 1° (Jorstad *et al.* 2004) instead of 5° results in extreme values of $B = 4.6 \cdot 10^2$ G and $u_e = 3.8 \cdot 10^{-14}$ erg cm^{-3} leading to a ratio u_B/u_e of $2 \cdot 10^{17}$, which seems very unrealistic.

4. Conclusion

The observed properties of synchrotron outbursts in microquasars appears to be quite similar, at least during some period of activity, with the behaviour of quasars. We find that timescales and physical sizes of the jet do scale with the black hole mass, but not strictly linearly as expected (e.g. Mirabel & Rodríguez 1998). For the observed timescales we find very roughly a square root dependence $\Delta t_{\text{obs}} \propto M_{\text{BH}}^{1/2}$, becoming more linear for the intrinsic length-scale Δl of the jet, which is corrected for orientation and relativistic effects. Apart from this scaling the physical properties of the jets, like the magnetic field and the electron energy density, are found to be very similar in all sources except GRS 1915+105, which has significantly higher values. The only clear difference we find between galactic and extragalactic jets is a harder electron energy distribution in microquasars, with an index s being clearly below 2 in Cyg X-3 and GRS 1915+105.

Our method of fitting multi-wavelength lightcurves with model outbursts is getting to the point where we can test different models and constrain the physics of relativistic jets. There are indications that the standard shock model of Marscher & Gear (1985) has to be modified to describe the observed evolution of synchrotron outbursts. Apart from the modifications proposed by Björnsson & Aslaksen (2000), we find evidence that the spectral turnover might rather be due to a low energy cut-off of the electron energy distribution than to synchrotron self-absorption during the initial phases of the outburst. More information, figures and animations at: <http://isdc.unige.ch/~turler/jets/>

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FELIX MIRABEL: Comment: The square of the mass dependency you find for the timescales is very interesting. It appears to be consistent with a similar relation that has been claimed for 3C 120.