Energetics of jets from X-ray binaries

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Abstract.
I discuss the energetics of synchrotron-emitting outflows, increasingly found to be present in many different classes of X-ray binary systems. It is shown that the outflow is likely to be comparable in power to the integrated X-ray luminosity, traditionally taken to be an indicator of the global mass-transfer rate. This is especially found to be the case in the (low)/hard states of black hole candidate systems. I conclude that jets are extremely important, energetically and dynamically, for the accretion process in the majority of known X-ray binary systems.

Keywords: Black hole physics – Stars: neutron – Binaries: close – ISM: jets and outflows

1. Introduction – the ubiquity of jets from X-ray binaries

Radio emission as a property of X-ray binary systems (XRBs) has developed in recent years from being a rare and unusual facet of their broadband spectrum to being recognised as a ubiquitous property of several classes of XRBs. In the early 1990s, it was still (almost) possible to discuss individually radio-emitting X-ray binaries (e.g. Hjellming & Han 1995), and numbers of systems in which collimated outflows, or jets, were directly observed could be counted on the fingers of one hand. As the 1990s drew on, more and more of these systems became resolved into such jets, and in the middle of the decade the apparent superluminal motions observed from GRS 1915+105 (Mirabel & Rodriguez 1994; see also Fender et al. 1999) and GRO J1655-40 (Tingay et al. 1995; Hjellming & Rupen 1995) established beyond doubt that XRBs could accelerate powerful flows to bulk velocities in excess of 0.9c. By 2000 we are beginning to realise that jets may be rather more ubiquitous than previously imagined (e.g. Mirabel & Rodriguez 1999; Fender & Hendry 2000; Fender 2000), and in Figs 1(a),(b) I summarise our (or at least my) current understanding of the empirical relation of radio emission to X-ray ‘state’ of the neutron star (NS) and black hole candidate (BHC) systems respectively. In addition to the relations

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Figure 1. (a): A qualitative sketch of the relation of jets to accretion in the three ‘types’ of neutron star XRB. In the low-field ‘Atoll’ sources the accretion rate is believed to be $< 10\%$ Eddington, except possibly during rare transient outbursts (e.g. Aql X-1); the evidence is marginal so far but it appears such sources are ‘radio on’ when in the ‘Island State’ (IS) in the X-ray colour-colour diagram (CD). The Z sources are believed to be accreting at a much higher rate, near Eddington, and are ‘radio on’ when on the ‘Horizontal Branch’ and maybe also, at a lower level, the ‘Normal Branch’ in the CD. Note that for both Atoll and Z sources the estimates of surface magnetic field are very uncertain. Finally, in the high-field X-ray pulsars no radio synchrotron emission has ever been detected; possibly this is due to truncation of the accretion disc a long way from the neutron star.

indicated in these figures, it seems that discrete, radio-emitting ejection events (in which the radio spectrum rapidly becomes optically thin) are associated with state transitions (including outbursts of transients).

While some areas of the coupling between accretion flow and jet are still empirically uncertain (the Atoll sources, the Intermediate/Very High state for BHCs), it seems that all XRBs except the high-field X-ray pulsars will, under the right conditions, produce a synchrotron-emitting jet. It is therefore an important question to address the significance of this jet, energetically and dynamically, for the process of accretion onto compact objects as a whole. One thing obvious from
Figure 1. (b): The qualitative relation of radio emission to X-ray ‘state’ in BHC XRBs: the low/hard state is found to produce a steady, flat- (or inverted-)spectrum jet, the soft state produces no detectable radio emission. The relation of $\dot{m}$ to these states is not certain (e.g. Homan et al. 2001); nor are the radio characteristics of the relatively rare ‘Intermediate/Very High’ states well determined.

inspection of Figs 1(a),(b) is the apparent anti-correlation between
the mass accretion rate, $\dot{m}$, traditionally estimated from X-ray studies alone, and the presence of a jet, in both NS and BHC systems (see also Belloni, Migliari & Fender 2000 and Homan et al. 2001 for further discussion).

### 2. Energetics from ‘equipartition’

In cases where it is possible to associate a given synchrotron luminosity with a given volume, the minimum energy associated with the event can be estimated assuming approximate equipartition. In this situation, the energy associated with the magnetic field is approximately equal to that associated with the electrons, and there is a corresponding equipartition magnetic field, $B_{eq}$. Below the equipartition field, the en-
ergy in particles ($\propto B^{3/2}$) dominates; above equipartition, the energy in the field ($\propto B^2$) dominates. While there is little obvious physical justification for assuming equipartition, it is useful in that it represents the case of maximal radiative efficiency for a synchrotron-emitting plasma.

One obvious way to associate luminosity and volume is by observing discrete ejection events sufficiently well that the rise time (and therefore maximum volume) and peak flux can be accurately measured. In Fig 2 we see an example of a sequence of repeated discrete ejection events, observed from radio through the mm band to the near-infrared band. Full details of the observations, and the application of equipartition estimations to these data, are found in Fender & Pooley (2000). The results of the equipartition calculations are presented in Table I. A more basic introduction to minimum energy requirements via equipartition can be found in e.g. Longair (1994).
From the estimates in Table I, it is clear that even in the minimum energy case, i.e., a pair plasma with no significant bulk kinetic energy, the power required for the jet is $3 \times 10^{38}$ erg s$^{-1}$. The integrated X-ray luminosity (presumably not coming from the jet?) at this time was $\sim 10^{39}$ erg s$^{-1}$, so we find that even in this case the ratio of jet power to total X-ray luminosity, $P_J/L_X \sim 0.3$. If we assume that the ejections share the bulk relativistic motion of the major ejections, then it seems $P_J > L_X$.

Spencer (1996) presents a summary of energy estimates based on the same application of equipartition to radio variability, for five XRB systems. In all cases the equipartition magnetic field lies in the range 0.01–1 Gauss, lower than that derived for the events from GRS 1915+105 considered above; however this may not be unreasonable considering that the peak emission from the longer events considered by Spencer would have originated in larger volumes. In all the five cases considered by Spencer (1996), the apparent jet power was at least equal to the integrated X-ray luminosity of the system.

In cases where the radio structure can be clearly resolved, the volume responsible for a certain luminosity can be estimated directly from images, and again equipartition applied. Spencer et al. (these proceedings) apply this method directly to the steady, resolved jets in Cygnus X-1, and Paredes et al. (2000) apply it to jets from the unusual system LS 5039, finding equipartition magnetic fields of 0.3 and 0.2 Gauss respectively. Both works further conclude that the energy associated with the resolved outflows is large, $> 10^{39}$ erg; however a major uncertainty in estimating the power in the outflow is associated with how continuously it must be generated.

### 3. Steady jets – energetics from radiative efficiency

Without large amplitude variability, or directly resolved jets, it is no longer possible to associate a given luminosity with a certain volume, and we must apply other arguments in order to estimate the total jet power. This is the situation we face in trying to estimate the power in jets from BHCs in the Low/Hard X-ray state, which produce a flat spectrum in the radio band with no large-amplitude variability (Fender 2000). In this case we may estimate the total jet power by (a) carefully measuring the extent of the synchrotron spectrum which it produces, and (b) introducing a radiative efficiency, $\eta$, which is the ratio of total to radiated power (in the jet’s rest frame). From this we can estimate the jet power as

$$P_J \sim L_J \eta^{-1} F(\Gamma, i)$$
Table I. Calculation of (synchrotron) radiative luminosity, equipartition magnetic field, total energy, jet power and mass-flow rate for the oscillations reported here, given different physical assumptions. $\Gamma$ is the bulk motion Lorentz factor; a filling factor of unity is assumed, otherwise the equipartition magnetic field would be high enough that radiative losses would be significant in the infrared. In these calculations a distance of 11 kpc and Doppler factors for relativistic bulk motion which are the same as those reported in Fender et al. (1999) are all assumed. Mass flow rate $\dot{M}_{\text{jet}}$ and jet power $P$ are based upon one ejection every 20 min. For more details, see Fender & Pooley (2000).

| Case | $\Gamma$ | $L_{\text{radiative}}$ (erg s$^{-1}$) | $B_{\text{eq}}$ (G) | $E_{\text{min}}$ (erg) | $P$ (erg s$^{-1}$) | $\dot{M}_{\text{jet}}$ (g s$^{-1}$) | $\eta$ |
|------|---------|--------------------------------------|-----------------|-----------------|-----------------|-----------------|------|
| $e^+:e^-$ | 5       | $3 \times 10^{37}$                  | 40              | $4 \times 10^{41}$ | $3 \times 10^{38}$ | 0.1             |      |
| $e^+:e^-$ | 5       | $4 \times 10^{39}$                  | 115             | $3 \times 10^{43}$ | $3 \times 10^{40}$ | 0.15            |      |
| $p^+:e^-$ | 5       | $3 \times 10^{37}$                  | 40              | $4 \times 10^{41}$ | $3 \times 10^{38}$ | $2 \times 10^{20}$ | < 0.1 |
| $p^+:e^-$ | 5       | $5 \times 10^{39}$                  | 115             | $1 \times 10^{46}$ | $8 \times 10^{42}$ | $4 \times 10^{21}$ | < 0.02 |

where $L_j$ is the total radiative luminosity of the jet, $\eta$ is the radiative efficiency, and $F(\Gamma, i)$ is a correction factor for bulk relativistic motion with Lorentz factor $\Gamma$ and Doppler factor $\delta$, ($F(\Gamma, i) \sim \Gamma \delta^{-3}$ – see Fender 2000).

3.1. Spectral extent and radiative luminosity

Starting from the reasonable assumption that all the emission observed in the radio band is synchrotron in origin, we can try to see how far this spectrum extends to other wavelengths. Firstly, it should be made clear that most systems have not been observed at $\nu < 1$ GHz, and while some low-frequency turnovers have occasionally been observed, there are no reported cases of a complete cut-off to the synchrotron emission at low radio frequencies. In any case, while a low-frequency cut-off is important for estimating the mass of the ejecta in the (by no means certain) case that there is a proton for each emitting electron, the radiative luminosity is dominated by the high-frequency extent of the synchrotron spectrum. Since the spectrum is unlikely to have a spectral index $\alpha < -1$ (where $S_\nu \propto \nu^\alpha$), then the most important observation is simply determination of the highest frequency at which synchrotron emission is observed.

In Fig 3 the broadband radio–optical spectra of eight XRB systems in (low/)hard X-ray states is presented; in all cases the spectra hint at an extension of the synchrotron spectrum to the near-infrared or even optical bands. There is a large amount of additional evidence for such a high-frequency extent to the spectrum, each piece of which may be considered ‘circumstantial’ but when gathered together presents a
Figure 3. Broadband radio-mm-infrared-optical spectra of eight black hole candidate XRBs in hard X-ray states (apart from GRS 1915+105, all of these can be considered to be the canonical ‘low/hard’ X-ray state). There seems to be clear evidence in all cases, where observable (i.e. not directly in Cyg X-1) for a continuation of the radio-mm synchrotron spectrum to at least the near-infrared band. Data and/or references for all systems in Fender (2000), except GX 339-4 (infrared–optical data from Corbel & Fender 2000), XTE J1550-564 (Corbel et al. 2000) and XTE J1118+480 (Fender et al. 2000).

compelling case (a lot of this evidence is presented in Fender 2000). Note also that observations of GRS 1915+105 (admittedly not a ‘typical’ system!), such as those shown in Fig 2, unambiguously establish that the synchrotron spectrum can extend to the near-infrared band.

Our best recent case is the low/hard state transient XTE J1118+480, which clearly shows excess emission at near-infrared and probably also optical wavelengths (Hynes et al. 2000) and whose radio spectrum smoothly connects to a sub-mm detection at 850 µm (Fender et al.
2000). In Fender et al. (2000) it is argued that in this case the synchrotron radiative luminosity is already $\geq 1\%$ of the bolometric X-ray luminosity. How important the total jet power is then depends on our estimates for the radiative efficiency, $\eta$.

3.2. Radiative efficiency

In Fender & Pooley (2000) a detailed study was made of the power required to maintain the repeated ejection events shown in Fig 2. In Table I, we also tabulate this radiative efficiency for the different cases considered; its maximum value is $\sim 0.15$. In one of the original works on the power in steady jets, Blandford & Königl (1979) determined that $\eta \sim \frac{1}{2} k \gamma (1 + \frac{2}{3} k \gamma \Lambda)^{-1}$, where $k \leq 1$ and $\Lambda = \ln(\gamma_{\text{max}}/\gamma_{\text{min}})$, $\gamma_{\text{max}}/\gamma_{\text{min}}$ being the upper and lower bounds of the electron energy spectrum respectively. Since it seems likely that $(\gamma_{\text{max}}/\gamma_{\text{min}})$ is in the range $10^2$–$10^4$, then $\eta < 0.15$. Celotti & Ghisellini (2001) find a comparable value for the radiative efficiency of AGN jets.

4. Comparison of jet power to accretion luminosity

The best-studied cases of clearly resolved (in time) ejection events, such as those presented in Fig 2, seem to require that the ratio of jet power to X-ray luminosity, $P_J/L_X > 0.3$. A more general study of large outbursts from five different systems shows that, via the simple equipartition arguments outlined above, $P_J/L_X > 1$ (Spencer 1996). Other applications of equipartition to XRB ejection events exist, and in all cases it seems that they imply the jet power is extremely significant.

Using a different, but not altogether unrelated, method of measuring the high-frequency extent of the synchrotron spectrum we find that for the BHC transient XTE J1118+480, $P_J/L_X > 0.01 \eta^{-1}$, where $\eta < 0.15$ for BHC systems in the canonical low/hard X-ray state. Since it seems that the relation of X-ray to radio flux in this state is comparable for all the systems (ie. the similarities in the broadband spectra of the sources presented in Fig 3 extend to at least the X-ray band), then it seems reasonable to conclude that $P_J/L_X \geq 0.1$ for all BHC XRBs in the low/hard X-ray state. Again it seems that the jet must be highly significant for the process of accretion.
5. Conclusions

Two different (but not entirely independent) approaches have revealed that a large fraction of the entire luminosity (radiative and mechanical) of some classes (this is important – we are no longer talking about individual ‘oddballs’) of X-ray binaries may be carried by the jet. This fraction is likely to be $> 0.1$ and may be $> 0.5$, i.e. the jet may even be the dominant power output channel. Since it is clear from studies of e.g. GRS 1915+105 that the disc–jet coupling is occurring in the inner few 100 km of the accretion flow, the extraction of such a large amount of energy (and presumably angular momentum) must have a dramatic effect on the accretion flow close to the compact object.

Based on this, it seems that models for accretion in X-ray binaries which at least parameterise such an outflow are needed. They are not entirely non-existent – for GRS 1915+105 (again!) both Nayakshin, Rappaport & Melia (2000) and Janiuk, Czerny & Siemiginowska (2000) have begun to consider the effect of a moderately powerful outflow on the accretion process. A more radical step has been taken by Markoff, Falcke & Fender (2000; see also these proceedings) in which almost the entire broadband spectrum of the BHC low state (excepting thermal emission in the optical – UV range) is explained by jet emission, and in which it is suggested that the X-ray power-law may even be synchrotron emission. This would be contrary to the generally accepted view that the X-ray power law in the low state arises in Comptonisation of ‘seed’ photons in a hot, thermal, corona. It is further worth noting that once mass-loss via jets is considered, and the empirical connections between X-ray ‘state’ and jet formation, as outlined in Figs 1(a),(b) recognised, then it is no longer clear that the global mass transfer rate can be inferred from X-ray observations alone.

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References

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