# Jets from X-ray binaries

Rob Fender

Astronomical Institute 'Anton Pannekoek', University of Amsterdam, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands

9 Jets from X-ray binaries	page 1
9.1 History	2
9.2 Physical properties of the jets	3
9.3 Ubiquity	14
9.4 Disc–jet coupling in black hole binaries	15
9.5 Disc-jet coupling in neutron star binaries	26
9.6 High energy / particle emission from jets	29
9.7 Interactions	32
9.8 Relation to other jet sources	34
9.9 On the origin of jets	36
9.10 Conclusions	39
Bibliography	40

#### 9.1 History

Relativistic outflows, or 'Jets', represent one of the most obvious, important and yet poorly-explained phenomena associated with accreting relativistic objects, including X-ray binaries. Originally recognised in images as long, thin structures apparently connected at one end to the nuclei of galaxies, it was soon established that they represent powerful flows of energy and matter away from accreting black holes and back to the Universe at large. From their earliest association with the most luminous sources in the Universe, the Active Galactic Nuclei (AGN), the conclusion could have been drawn that jets were a common consequence of the process of accretion onto relativistic objects. Nevertheless, their association with the analogous accretion processes involving stellar-mass black holes and neutron stars was not systematically explored until the past decade or so.

Although it is now clear that the electromagnetic radiation from X-ray binary jets may extend to at least the X-ray band, historically the key observational aspect of jets is their radio emission. High brightness temperatures (see section 9.2), 'nonthermal' spectra and polarisation measurements indicate an origin as synchrotron emission from relativistic electrons. Following the discovery of luminous binary X-ray sources in the 1960s and 1970s, radio counterparts were associated with the brightest of these, e.g. Sco X-1 (Hjellming & Wade 1971a), Cyg X-1 (Hjellming & Wade 1971b) and the outbursting source Cyg X-3 (Gregory et al. 1972 et seq.). However, it was not until

radio observations of the strong radio source associated with the unusual binary SS 433 revealed a *resolved* radio source that the field of X-ray binary jets really opened up (Spencer 1979; see also Hjellming & Johnston 1981a,b). Outbursts of 'soft X-ray transients' were also often associated with strong, transient radio emission (e.g. A0620-00: Owen et al. 1976; GS 1124-583: Ball et al. 1995; see also Hjellming & Han 1995; Kuulkers et al. 1999; Fender & Kuulkers 2001).

In the 1990s the study of jets from X-ray binaries entered a new phase with the discovery of apparent superluminal motions in the outflow from the bright X-ray transient 'microquasar' GRS 1915+105 (Mirabel & Rodríguez 1994; see also Mirabel & Rodríguez 1999; Fender et al. 1999a; Rodríguez & Mirabel 1999; Fender et al. 2002). For the first time it was clear that the jets from X-ray binaries can also exhibit the kind of significantly relativistic (Lorentz factors  $\Gamma \geq 2$ , where  $\Gamma = (1 - \beta^2)^{-1/2}$  and  $\beta = v/c$ ) velocities observed in the jets of AGN, and not just the mildly relativistic velocity of  $\sim 0.26c$  ( $\Gamma = 1.04$ ) observed in SS 433. Exactly how relativistic these jets are will be discussed later. Shortly afterwards a second superluminal galactic source, GRO J1655-40, was discovered (Tingay et al. 1995; Hjellming & Rupen 1995).

Since this period detailed investigations of the jets from X-ray binaries, both in the radio band and at shorter wavelengths, have revealed a rich phenomenology and clear patterns of behaviour which have provided unique insights into the coupling of accretion and outflow close to relativistic objects. Nevertheless, the deeper we look the more complex the behaviour becomes, and this is a rapidly advancing field. In this review I shall attempt, subjectively, to describe the state of the research as it is at the beginning of 2003.

In Figs 9.1 and 9.2 are presented recent sequences of observations of transient relativistic outflows from black hole binaries. Fig 9.1 presents radio radio images of relativistic ejections from three outbursting X-ray binaries on sub-arcsecond angular scales. Fig 9.2 presents X-ray images of arcsecond-scale jets moving away from the transient XTE J1550-564 up to four years after the original ejection event, observed with Chandra.

## 9.2 Physical properties of the jets

In the following I shall briefly outline out understanding of the emission mechanisms in X-ray binary jets, and how we can estimate important physical quantities from the most basic of observations.

#### 9.2.1 Emission mechanism

The radio jets observed from X-ray binaries emit via the synchrotron process. We are drawn to this conclusion by their 'nonthermal' spectra, high brightness temperatures and, in some cases, high degree of linear polarisation. In the following we will illustrate how some fundamental parameters, e.g. the magnetic field and energy associated with ejection events, can be estimated from the most basic observations. For a more detailed explanation and exploration of synchrotron emission the reader is directed to e.g. Longair (1994).

Bright events associated with e.g. X-ray state changes and X-ray transients reveal an optically thin spectrum above some frequency, from which the underlying

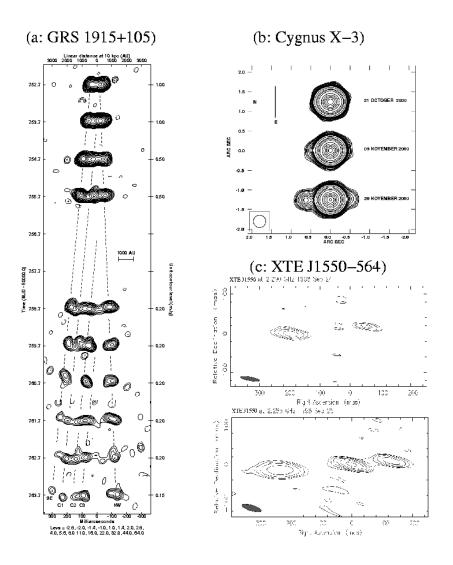


Fig. 9.1. Radio images of relativistic jets from X-ray binaries. Panel (a) shows a sequence of images of 'superluminal' relativistic ejections from GRS 1915+105 observed with MERLIN (Fender et al. 1999a). Panel (b) is a sequence of slower, arcsec-scale jets from Cyg X-3 (Martí et al. 2002), which may be the jet-ISM interaction zones of the inner, more relativistic jet (Mioduszewski et al. 2000). Panel (c) presents two VLBI images of XTE J1550-564 shortly after the major flare in 1998 which was probably responsible for the formation of radio and X-ray lobes (see Fig 9.2) four years later; from Hannikainen et al. (2001).

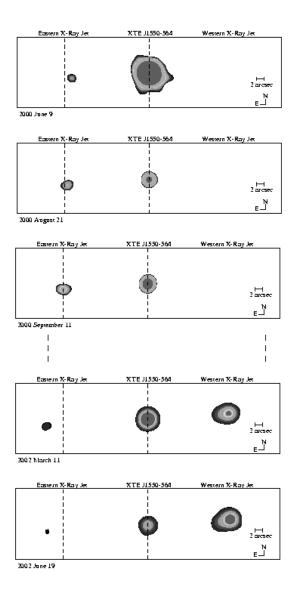


Fig. 9.2. Chandra images of moving X-ray jets from the black hole transient XTE J1550-564 (Corbel et al. 2002; see also Kaaret et al. 2002 and Tomsick et al. 2002). The core is the central component, the 'approaching' jet to the left (East) and the 'receding' jet to the right (West). These remarkable observations are the first detections of relativistic proper motions in X-rays, and demonstrate unambiguously that X-ray binary jets can accelerate electrons to extremely high energies and as a result are sources of beamed X-rays. Note that in the top panel the apparent fluxes are reduced by the presence of a grating; in fact the eastern jet was brighter at this epoch than at any time subsequently.

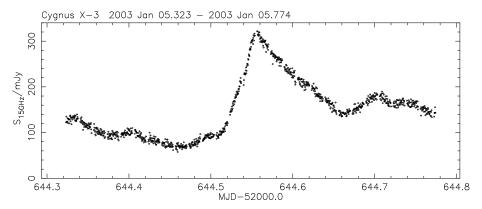


Fig. 9.3. Observation of a 'clean' radio flare event from the jet source Cyg X-3 at 15 GHz. The rise time of the event  $\sim 0.04$  d, allows an estimation of the size of the region associated with the event, and thus the minimum energy. Observations from the Ryle Telescope (Guy Pooley, private communication).

electron population can be derived. If the underlying electron distribution is a power law of the form  $N(E)dE \propto E^{-p}dE$  then observations of the spectral index  $(\alpha = \Delta \log S_{\nu}/\Delta \log \nu$ , i.e.  $S_{\nu} \propto \nu^{\alpha})$  in the optically thin part of the synchrotron spectrum can directly reveal the form of this electron distribution:  $p = 1 - 2\alpha$ .

Observed optically thin spectral indices  $-0.4 \ge \alpha \ge -0.8$ , indicate  $1.8 \le p \le 2.6$ . This is the same range derived for the majority of AGN jets and also for synchrotron emission observed in other astrophysical scenarios e.g. supernova remnants, and is consistent with an origin for the electron distribution in shock acceleration (e.g. Longair 1994; Gallant 2002).

## 9.2.2 Minimum energy estimation

Association of a given synchrotron luminosity with a given volume (either by direct radio imaging or by measurement of an associated variability timescale) allows estimation of the minimum energy associated with the synchrotron-emitting plasma (Burbidge 1959), at a corresponding 'equipartition' magnetic field.

Longair (1994) gives a clear explanation of the calculation of the minimum energy and corresponding magnetic field, and the interested reader is directed there. Repeating some of his useful formulae, a lower limit to the energy associated with a finite volume of synchrotron emitting plasma can be obtained from a simple estimate of the monochromatic luminosity at a given frequency which is associated with that volume:

$$E_{\rm min} \sim 8 \times 10^6 \eta^{4/7} \left(\frac{V}{{\rm cm}^3}\right)^{3/7} \left(\frac{\nu}{{\rm Hz}}\right)^{2/7} \left(\frac{L_{\nu}}{{\rm erg \ s}^{-1} {\rm Hz}^{-1}}\right)^{4/7} \quad {\rm erg}$$
 (9.1)

where  $\eta = (1 + \beta)$  and  $\beta = \epsilon_{\rm p}/\epsilon_{\rm e}$  represents the ratio of energy in protons to that in electrons, and assuming p = 2. It is generally accepted that  $\beta \sim 0$  and therefore  $\eta \sim 1$ , often with little serious justification. In the more common case where we do not image the source but rather infer its size from the rise time  $\Delta t$  of an event (i.e.

using  $V = (4/3)\pi(c\Delta t)^3$  with a flux density  $S_{\nu}$  originating at an estimated distance d, the formula can be rewritten as

$$E_{\rm min} \sim 3 \times 10^{33} \eta^{4/7} \left(\frac{\Delta t}{\rm s}\right)^{9/7} \left(\frac{\nu}{\rm GHz}\right)^{2/7} \left(\frac{S_{\nu}}{\rm mJy}\right)^{4/7} \left(\frac{d}{\rm kpc}\right)^{8/7} \quad {\rm erg} \quad (9.2)$$

The related mean power into the ejection event

$$P_{\min} = \frac{E_{\min}}{\Delta t} \sim 3 \times 10^{33} \eta^{4/7} \left(\frac{\Delta t}{\text{s}}\right)^{2/7} \left(\frac{\nu}{\text{GHz}}\right)^{2/7} \left(\frac{S_{\nu}}{\text{mJy}}\right)^{4/7} \left(\frac{d}{\text{kpc}}\right)^{8/7} \quad \text{erg s}^{-1}(9.3)$$

This minimum energy condition is achieved at so-called 'equipartition', when the energy in particles and magnetic field is comparable. This field can be approximated by

$$B_{\rm eq} \sim 30\eta^{2/7} \left(\frac{S_{\nu}}{\rm mJy}\right)^{2/7} \left(\frac{d}{\rm kpc}\right)^{4/7} \left(\frac{\Delta t}{\rm s}\right)^{-6/7} \left(\frac{\nu}{\rm GHz}\right)^{1/7} \quad G$$
 (9.4)

Note that this field is not, as can sometimes be presumed, a *minimum* magnetic field but rather the field corresponding to the minimum energy – i.e. increase or decrease the field and the energy required to produce the observed synchrotron emission increases. The Lorentz factors of electrons (or positrons) emitting synchrotron emission at a given frequency can be estimated by:

$$\gamma_e \sim 30 \left(\frac{\nu}{\text{GHz}}\right)^{1/2} \left(\frac{B}{\text{G}}\right)^{-1/2}$$
 (9.5)

Fig 9.3 shows a clean radio flare event from the X-ray binary jet source Cyg X-3. The observation is at 15 GHz, has a rise time of  $\sim 3500$  s, an amplitude of  $\sim 200$  mJy and Cyg X-3 lies at an estimated distance of  $\sim 8$  kpc. Using the above approximations we find a minimum energy associated with the event of  $E_{\rm min} \sim 5 \times 10^{40}$  erg, and a corresponding mean jet power during the event of  $\sim 10^{37}$  erg s<sup>-1</sup>, many orders of magnitude greater than the observed radiative luminosity. The corresponding equipartition field can be estimated as  $\sim 0.5$  Gauss, in which field electrons radiating at 15 GHz must have Lorentz factors  $\gamma \sim 150$ .

It should be stressed that the inner regions of jets from X-ray binaries have relativistic Doppler factors (see below) considerably different from unity resulting from relativistic bulk motions, whereas the above estimations are based upon rise times, flux densities and frequencies as measured in the comoving frame. In such cases the observed quantities need to be corrected to the comoving frame before the estimates can be made. In addition, in such cases the kinetic energy associated with the ejection needs to be taken into account. This kinetic energy component is given by:

$$E_{\rm kin} = (\Gamma - 1)E_{\rm int} \tag{9.6}$$

– i.e. for a bulk Lorentz factor  $\Gamma > 2$  (by no means unreasonable – see below) kinetic dominates over internal energy.

## 9.2.3 Flare events

Flare events such as that presented in Fig 9.3 are believed to result from the short-term injection of energy and particles into an expanding plasma cloud, presumably in the form of a jet. Such events are characterised by optically thin spectra and are associated with e.g. X-ray transients and persistently flaring sources such as Cyg X-3 and GRS 1915+105. From Fig 9.3 it is clear that rise and decay phases can be quite clearly defined. In the 'synchrotron bubble' model (van der Laan 1966; Hjellming & Johnston 1988; Hjellming & Han 1995 and references therein) the rise phase corresponds to a decreasing optical depth at frequencies which were initially (synchrotron-)self-absorbed; observational characteristics would be an inverted radio spectrum during the rise phase, and possible Doppler effects on the profile (since the effect takes place in a different frame to the observer). An alternative explanation is that the rise phase represents a finite period of particle injection/acceleration in the outflow; the characteristics of such a phase would be an optically thin spectrum and a duration at least coupled to events more or less in the observer's frame e.g. the X-ray emission arising from the accretion disc. It seems (to this author) that there are probably observed events of both types. Note that time delays in the propagation of a shock (or other particle acceleration phenomena) through the differing 'photospheres' of an outflow may (misleadingly) mimic the 'synchrotron bubble' effect (see discussion in Klein-Wolt et al. 2001).

The monotonic decay observed after a few days in the radio events from X-ray transients (see below) seems to be primarily due to adiabatic expansion losses, the key signature of which is the same decay rate at all frequencies. Significant loss of energy through the synchrotron emission process itself, or via inverse Compton scattering, results in a more rapid decay at higher frequencies (spectral steepening). The fact that adiabatic losses dominate reveals clearly that the synchrotron radiation observed from such events is only a small fraction of the total energy originally input.

## 9.2.4 Speed

Mirabel & Rodríguez (1994) first reported apparent superluminal motions from a galactic source, GRS 1915+105. This apparent velocity ( $\beta_{obs}$ ) is related to the observed proper motion by

$$\beta_{\rm obs} \sim \left(\frac{\mu}{170 \text{ mas d}^{-1}}\right) \left(\frac{d}{\text{kpc}}\right)$$
 (9.7)

The apparent velocity is related to the intrinsic velocity  $(\beta_{int})$  by:

$$\beta_{\text{obs}} = \frac{\beta_{\text{int}} \sin \theta}{1 \mp \beta_{\text{int}} \cos \theta} \tag{9.8}$$

where  $\theta$  is the angle of the flow to the line of sight ( $\mp$  refer to approaching and receding components respectively). Apparent superluminal motion (i.e.  $\beta_{obs} > 1$ ) requires  $\beta_{int} \geq 0.7$ , indicating that at least mildly relativistic intrinsic velocities are required to achieve the effect (or a badly overestimated distance!). The associated relativistic Doppler shift is given by

$$\delta = \Gamma^{-1} (1 \mp \beta_{\text{int}} \cos \theta)^{-1} \tag{9.9}$$

where  $\Gamma$  is the bulk Lorentz factor of the flow. This  $\Gamma$  term represents time dilation at relativistic velocities and means that in certain circumstances (probably the case for the superluminal jet sources GRS 1915+105 and GRO J1655-40) both jets can be redshifted.

Given observed proper motions of jets, how can we estimate  $\beta_{\rm int}$ ? As described in Mirabel & Rodríguez (1994), measurement of  $\mu_{\rm app}$  and  $\mu_{\rm rec}$  allows a determination of the following product:

$$\beta_{\rm int} \cos \theta = \frac{(\mu_{\rm app} - \mu_{\rm rec})}{(\mu_{\rm app} + \mu_{\rm rec})} \tag{9.10}$$

where  $\theta$  is the angle of the ejection to the line of sight and  $\mu_{app}$ ,  $\mu_{rec}$  are the approaching and receding proper motions respectively (see also Rees 1966; Blandford, McKee & Rees 1977).

Once the proper motions are measured, the angle of ejection,  $\theta$ , and consequently the intrinsic velocity,  $\beta$ , are uniquely determined for every distance since

$$\tan \theta = \frac{2d}{c} \left( \frac{\mu_{\rm app} \mu_{\rm rec}}{\mu_{\rm adp} - \mu_{\rm rec}} \right) \tag{9.11}$$

and the product  $\beta_{\text{int}} \cos \theta$  is already known.

The variation of  $\beta_{\rm int}$  and  $\theta$  as a function of distance for GRS 1915+105 was presented in Fender et al. (1999a). There is a maximum distance to the source corresponding to  $\beta_{\rm int} = 1$  (i.e.  $\Gamma = \infty$ ):

$$d_{\text{max}} = \frac{c}{\sqrt{(\mu_{\text{add}}\mu_{\text{rec}})}} \tag{9.12}$$

At this upper limit to the distance you also find the maximum angle of the jet to the line of sight.

$$\theta_{\text{max}} = \cos^{-1} \frac{(\mu_{\text{app}} - \mu_{\text{rec}})}{(\mu_{\text{app}} + \mu_{\text{rec}})} \tag{9.13}$$

In addition to the proper motions and Doppler-shifting of frequencies, there is a boosting effect due to a combination of Doppler and relativistic aberration effects, both contained in the relativistic Doppler factor (eqn. 9.9). An object moving at angle  $\theta$  to the line of sight with velocity  $\beta$  (and resultant Lorentz factor  $\Gamma$ ) will have an observed surface brightness  $\delta^k$  brighter, where 2 < k < 3 (k = 2 corresponds to the average of multiple events in e.g. a continuous jet, k = 3 corresponds to emission dominated by a singularly evolving event). Therefore the ratio of flux densities from approaching and receding knots – measured at the same angular separation from the core, so as to sample the knots at the same age in their evolution – will be given by:

$$\frac{S_{\rm app}}{S_{\rm rec}} = \left(\frac{\delta_{\rm app}}{\delta_{\rm rec}}\right)^{k-\alpha}$$

where  $\alpha$  is the spectral index (to compensate for the spectral shape for different Doppler shifts). For a more detailed discussion see e.g. Blandford et al. 1977; Hughes 1991; Mirabel & Rodríguez 1999; Fender 2003).

## 9.2.4.1 Observed speeds of steady jets

There are basically no direct measurements of the speeds associated with the 'steady' jets inferred to exist in the low/hard state of black holes (see section 9.4.1), and possibly also in the 'plateau' state of GRS 1915+105 and the hard states of some neutron star Atoll sources. Nevertheless, there are some clues that the jets may be mildly, but not highly, relativistic. Stirling et al. (2001), in direct imaging of the mas-scale jet from Cyg X-1 in the low/hard state, inferred a minimum speed of  $\beta \geq 0.6$  based upon the one-sidedness of the jet. Gallo, Fender & Pooley (2003) have performed Monte Carlo simulations in order to investigate the effect of significant Doppler boosting on the observed radio : X-ray correlation in the low/hard state (see Fig 9.9). They found that intrinsic velocities for the radio emitting component of v > 0.8c would probably result in a larger spread in the correlation than is observed – therefore the bulk Lorentz factor  $\Gamma$  of the steady radio-emitting jets is likely to be < 2 (strictly true only for cases in which the X-rays are not significantly beamed).

It is perhaps incorrect to place the neutron star Z sources in this section, since they may be just as well considered 'persistent transients', like GRS 1915+105. Whatever the classification, the observations of Sco X-1 (Fomalont et al. 2001a,b) present a fascinating demonstration that the velocity of the flow from the accretion region may be rather different from that observed for the radio-emitting knots. Specifically, an unseen underlying flow with Lorentz factor  $\geq 2$  is inferred to be powering a particle acceleration zone which is itself moving away from the binary with a mildly relativistic (and non-constant) speed of  $\sim 0.5c$ .

## 9.2.4.2 Observed speeds of transient jets

In 1994 VLA observations of apparent superluminal motions from the black hole transient GRS 1915+105 demonstrated unequivocally that X-ray binaries could produce highly relativistic jets (Mirabel & Rodríguez 1994). Since then, a further three or four superluminal sources have been discovered (GRO J1655-40: Tingay et al. 1995; Hjellming & Rupen 1995; XTE J1748-288: Rupen, Hjellming & Mioduszewski 1998; XTE J1550-560: Hannikainen et al. 2001; Corbel et al. 2002; V4641 Sg: Hjellming et al. 2000a; Orosz et al. 2001), and there is certainly no indication that highly relativistic ejections are unusual for black hole X-ray transients.

But how relativistic are these events? Following Mirabel & Rodríguez (1994) it was widely accepted that X-ray binary jets could be characterised by Lorentz factors  $\sim 2$  (i.e. while significantly relativistic, considerably less so than the most extreme examples of AGN jets). In Fender et al. (1999) it was however shown that a much wider range of bulk Lorentz factors was possible, at least for GRS 1915+105. Fender (2003) has recently shown that direct measurements of proper motions of radio components cannot be used to constrain (specifically, to place an upper limit on) the Lorentz factor of the flow. In Fig 9.4 the solutions to  $\beta$ ,  $\theta$ ,  $\Gamma$  and  $\delta_{\rm app,rec}$  are plotted as a function of distance to the two 'superluminal' sources GRS 1915+105 and GRO J1655-40, along with the best distance estimates. It is clear that within uncertainties in the distance estimates (which are already relatively accurate), the Lorentz factor of the jets cannot be constrained by observations of proper motions. Nevertheless, Fender & Kuulkers (2001) concluded that the mean bulk Lorentz factor for transients was likely to be  $\leq 5$  since higher values would probably destroy the

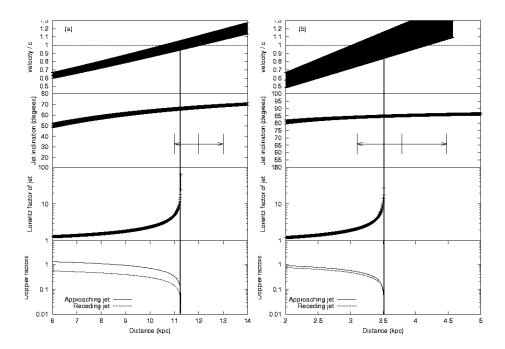


Fig. 9.4. Variation of solutions to velocity, angle to line of sight, Lorentz factor and Doppler factors for GRS 1915+105 and GRO J6155-40, as a function of distance, based upon observations of proper motions. When compared with the (relatively accurate) distance estimates it is clear that it is impossible to constrain the Lorentz or Doppler factors of the flow by such measurements. From Fender (2003).

observed correlation between radio and X-ray peak fluxes (unless X-ray were also beamed by the same Lorentz factor, implying inclination selection effects in our source lists). There are a couple of caveats to this statement: first it has been shown at least for XTE J1550-564 that jets decelerate steadily as they propagate away from the binary (Corbel et al. 2002; Kaaret et al. 2003; see Fig 9.5); secondly, the observations of Sco X-1 (Fomalont et al. 2001a,b) show us that the Lorentz factor (and hence boosting) of the energising beam may be very different to that of the actual radio emitting region (consider also V4641 Sgr in this scenario – Orosz et al. 2001 and discussion therein).

No proper motions have ever been observed from a neutron-star X-ray transient. The only concrete hint, physical analogies aside, that they may be relativistic, is the lower limit of  $\geq 0.1c$  for the arcsec-scale jet of Cir X-1 (Fender et al. 1998) which undergoes a transient-like outburst every 16.6 days.

Need the jet velocities be constant? In SS 433 this seems not to be the case – Eikenberry et al. (2002) have shown that the velocity of the jet may change by more

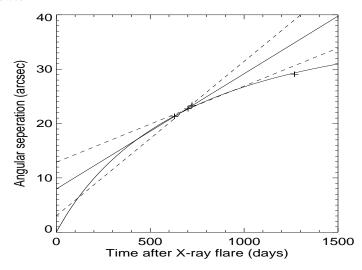


Fig. 9.5. Deceleration of X-ray jets from XTE J1550-564. Comparing a lower limit on the early proper motions on VLBI scales (Hannikainen et al. 2001) with subsequent measurements of the X-ray jets (Fig 2) with Chandra, indicates a steady slow-down of the jets. A large fraction of the dissipated kinetic energy seems to be channeled into particle acceleration. From Kaaret et al. (2003); see also Corbel et al. (2002) and Tomsick et al. (2003).

than 10%. In addition, in XTE J1550-564 (Corbel et al. 2002; Fig 9.2) we clearly observe deceleration of the jet (Fig 9.5). Since this deceleration probably occurs as a consequence of interactions with the ISM, it is likely to occur to varying degrees in all X-ray binaries, suggesting that measured velocities may always be a function of time (a relevant point here is that there's nothing to indicate that either the original flare event or the surrounding ISM are particularly unusual in any way).

To summarise, at this stage it seems that the 'steady' jets associated with the low/hard state of black holes and, by analogy, possibly with some neutron star Atoll sources are only mildly relativistic. The jets associated with X-ray transients seem almost certain to have considerably higher Lorentz factors which, however, decrease with time as the jet interacts with the ISM (see also section 9.7). Whether or not there is a smooth continuum of velocities, or a 'switch' from mildly- to highly-relativistic flow speed (e.g. Meier et al. 1997) is at present unclear.

#### 9.2.5 Orientation and precession

To date it has been assumed, quite reasonably in the absence of other information, that the jet inclination is perpendicular to the plane of the binary. However, at least two jet sources (GRO J1655-40 and V4641 Sgr) appear to show significant misalignments (Maccarone 2002 and references therein).

The clearest example of a precessing jet is SS 433. The  $\sim 162.5$ -day precession of these jets (e.g. Margon 1984; Eikenberry et al. 2001) has been assumed to reflect the precession period of the accretion disc (see e.g. Ogilivie & Dubus 2001 for a discussion). Hjellming & Rupen (1995) suggested a precession period for GRO J1655-

40 which was very close to the subsequently determined orbital period; similarly there seems to be marginal evidence for precession in the jets of GRS 1915+105 (Fender et al. 1999; see also Rodríguez & Mirabel 1999). Kaufman Bernado, Romero & Mirabel (2002) and Romero, Kaufman Bernado & Mirabel (2002) have suggested that precessing jets from X-ray binaries may result in recurrent 'microblazar' activity, possibly manifesting itself as high energy (gamma ray) flashes as the beam crosses the line of sight. Fender (2003) has discussed the possible signature of precession on the proper motions observed from a jet source.

#### 9.2.6 Composition

Since, with one exception, we have only identified the synchrotron emission from the leptonic (electrons and/or positrons) component in X-ray binary jets (a statement also true for AGN), we have little direct information on their baryonic content (or lack thereof). The one exception is of course SS 433, whose jets are associated with a variety of emission lines in optical, infrared and X-ray spectra (e.g. Margon 1984; Marshall, Canizares & Schulz 2002).

Why is SS 433 the only jet source with such emission lines? One possible interpretation is that all the other jets (which also seem to have considerably higher bulk velocities than the  $\sim 0.26c$  consistently measured for SS 433) have little or no baryonic content and are dominated by electron: positron pairs. This in turn would imply that the majority of the mass in the accretion flow never escapes from the system. It is interesting to note that extended (> arcsec) X-ray jets have been observed from both SS 433 and XTE J1550-564 (Migliari, Fender & Mèndez 2002; Corbel et al. 2002; Kaaret et al. 2003; Tomsick et al. 2003; see Fig 9.14). The jets from SS 433 reveal strong emission lines from highly ionised Iron and are consistent with thermal emission from a plasma at  $\sim 10^7 \mathrm{K}$  whereas those from XTE J1550-564 reveal a featureless continuum which is consistent with an extrapolation of the synchrotron spectrum from the radio band. Mirabel et al. (1997) have discussed effects which would result in atomic emission lines from significantly relativistic jets being very hard to detect, due to extreme Doppler broadening in the jet plasma. In addition, Fender (2003) has shown that the Doppler factors of the jets are very poorly constrained, so that we basically don't know where to look for such lines.

An alternative approach to the composition is to investigate the energetics associated with carrying along a population of 'cold' protons in the relativistic flow. Fender & Pooley (2000) did this for the radio–mm–infrared oscillations from GRS 1915+105 and found the power required to accelerate the proton population to a bulk velocity  $\Gamma=5$  was so large that the ejections were probably at a considerably lower bulk Lorentz factor or did not have a large baryonic component. In a related approach, Celotti & Ghisellini (2003) have concluded that a baryonic component is required for the jets of FRI-type radio galaxies in order to carry most of the power.

An alternative approach to looking for emission lines or balancing energetics is polarisation – in particular circular polarisation holds the promise of a unique insight into the conditions in the emitting plasma (e.g. Wardle et al. 1998; Wardle & Homan 2001). Circular polarisation has been detected from three X-ray binaries – SS 433 (Fender et al. 2000), GRS 1915+105 (Fender et al. 2002) and GRO J1655-40 (Macquart et al. 2002). However, the current state of data and models is not

enough to place strong quantitative constraints on the composition of the jets, since the observed circular polarisation could arise in both a pair-dominated and baryonic plasma. Right now it seems that we are no closer to convincingly determining the composition of jets from X-ray binaries, and the detection of Doppler-shifted emission (or annihilation) lines from other systems must remain a high priority observation.

## 9.3 Ubiquity

While clearly an important physical process for some X-ray binaries, in order to establish the broader significance of jets from X-ray binaries it is important to have some idea of their ubiquity. Although it is always preferable to have directly resolved images of jets, in many cases it is enough (or at least the best we can do) to infer the presence of a jet from more circumstantial evidence – in most cases this will be e.g. the presence of radio emission with a certain spectrum or type of variability. This approach can be justified by considering the following: the (comoving) brightness temperature  $T_{\rm B}$  of an object of physical size R, measured with a flux density  $S_{\nu}$  at a frequency  $\nu$ , and lying at a distance d, is given by the following expression:

$$T_{\rm B} = 2 \times 10^{13} \left(\frac{S_{\nu}}{\rm mJy}\right) \left(\frac{d}{\rm kpc}\right)^2 \left(\frac{R}{R_{\odot}}\right)^{-2} \left(\frac{\nu}{\rm GHz}\right)^{-2} \quad K \tag{9.14}$$

Setting a maximum brightness temperature of  $T_{\rm B} \leq 10^{12}$  (above which inverse Compton losses become catastrophic, at least for steady states), this can be rearranged to derive a minimum size for an emitting region, based upon a measured radio flux density and a distance estimate.

$$R \ge 4 \left(\frac{S_{\nu}}{\text{mJy}}\right)^{1/2} \left(\frac{d}{\text{kpc}}\right) \left(\frac{\nu}{\text{GHz}}\right)^{-1} R_{\odot}$$
 (9.15)

A typical  $\sim 5$  GHz detection of a 'weak' radio counterpart to an X-ray binary is at the  $\sim$  mJy level, and such sources typically lie at distances of  $\geq 5$  kpc. Plugging in those numbers produces a minimum size for the emitting region  $R \geq 8R_{\odot}$ . Typical binary separations for low mass X-ray binaries are smaller than this; even the binary separation of Cyg X-1 – a high-mass X-ray binary in a relatively large 5.6-day orbit – is unlikely to be  $\geq 15R_{\odot}$ . Therefore we have a relativistic plasma (since the emission mechanism is synchrotron) with a volume larger than that of the binary system. Such a plasma will be unconfinable by any known component of the binary system, and thus will flow out from the system. Expansion losses will monotonically reduce the flux observed at optically thin frequencies, and this appears to be the case for the 'synchrotron bubble' events observed from X-ray transients, repeatedly and clearly resolved by radio interferometers into two-sided outflows. For the steady sources the same expansion losses require that in order to observe persistent radio emission, this plasma must be continually replenished – therefore we are drawn to conclude that an outflow of relativistic plasma is present. In nearly all cases, when this radio-emitting region has been directly resolved, it is in the form of either steady jet-like structures or outflowing 'blobs'; by Occam's razor we conclude that this is the most likely scenario for most, if not all, radio emission from X-ray binaries (but see Rupen, Mioduszewski & Hjellming 2002 for the rather different case of CI Cam). Note that it is well known that beamed (ie. relativistically aberrated) emission can display apparent brightness temperatures  $>> 10^{12}$  K, but invoking relativistic motion to explain away a jet is rather contradictory. Finally, the same simple jet models originally developed for AGN naturally reproduce the spectrum and luminosity of radio emission observed from these systems.

So, allowing ourselves to make the assumption that radio emission is associated with jets, we can draw the following conclusions, which will be discussed in greater detail below:

- All black hole systems which are either in the 'low/hard' X-ray state, or are undergoing a major transient outburst, are associated with the formation of a jet (albeit possibly of different 'types'). Thus the majority of known binary black holes are, or have been in the past, associated with a jet.
- The six brightest low magnetic field neutron star systems, the 'Z sources', are all associated with jets in some parts of the 'Z' track. The lower luminosity, low magnetic field systems, which may be crudely lumped together as 'Atoll' sources, may be associated with radio emission (although as with black holes there may be bright soft states without jets), implying that the lack of radio detections of the majority is a sensitivity issue.
- The high magnetic field neutron stars, including all but two of the accreting X-ray pulsars, are *not* associated with radio emission

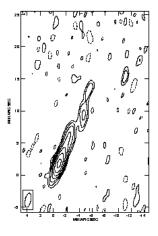
Adding up the numbers, this author concludes that the evidence for a jet is very strong in about thirty X-ray binaries (10–15% of the currently known population), but that it is rather likely that jets are present in up to 70% of the systems (basically all except the high magnetic field X-ray pulsars, and a small number of black hole and neutron star systems which are in persistent 'soft' states).

## 9.4 Disc-jet coupling in black hole binaries

One of the richest areas of X-ray binary jets research in the past few years has been the disc:jet coupling, i.e. the relation between inflow and outflow. Some early clues to the phenomenology outlined below were reported earlier in the literature – e.g. some low/hard state transients were known to exhibit flat-spectrum 'second stage' radio emission (Hjellming & Han 1995 and references therein) which we would now associate with the compact jet in the core. Furthermore, McCollough et al. (1999) already reported the bimodal behaviour of the radio:X-ray correlations in Cyg X-3, undoubtedly related to the changing disc:jet coupling outlined below.

Black holes exhibit, broadly speaking, several different kinds of X-ray 'state'. The two most diametrically opposed, which serve to illustrate the relation of jet formation to accretion, can be briefly summarised as:

• Low/Hard (and 'Off') state: in this state the X-ray spectrum is dominated by a broadband component which can be fit with a power-law of photon index ~ 1.6, often with a cut-off around 100 keV. Minor additional components to the X-ray spectrum include (sometimes) a weak 'black body' (accretion disc) component, a 'reflection' component and a relatively weak gamma-ray tail. The X-ray power spectra show up to 40% r.m.s. variability with a 'break' at frequencies of around a few Hz.



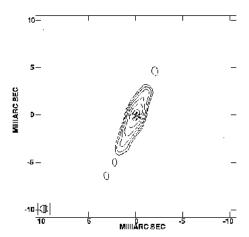


Fig. 9.6. AU-scale jets in persistent hard X-ray states, imaged with the VLBA. The left panel reveals a one-sided jet from Cygnus X-1 in the classical 'low/hard' X-ray state (Stirling et al. 2001). The right panel shows the quasi-steady jet from GRS 1915+105 in hard 'plateau' states (Dhawan, Mirabel & Rodríguez 2000).

• 'High/Soft' state: in this state the X-ray spectrum is dominated by a 'black body' component with a temperature around a few keV, with additional line features and a relatively strong gamma-ray tail. The X-ray power spectrum shows much less variability, and can be characterised by a power-law with an r.m.s. variability of only a few %.

Further details of black hole states may be found in the chapters by van der Klis (chapter 2), and McClintock & Remillard (chapter 4).

There are also 'Intermediate' and 'Very High' states which actually both appear to be quasi-steady states which share some of the characteristics of both of the above states, but – crucially for their relation to jet formation – which are *much softer* than the regular 'Low/Hard' state. Homan et al. (2001) have shown that such states can actually occur at a wide variety of luminosities.

#### 9.4.1 Steady jets in 'low/hard' and 'quiescent' states

The radio, and hence jet, properties of the low/hard state black holes can be summarised thus: a 'flat' spectrum (spectral index  $\alpha \sim 0$ ) extending through and beyond the radio band, linear polarisation at a level of  $\sim 1\text{--}3\%$  and variability correlated with the X-ray flux. These broad properties, significantly different from those associated with transient ejection events, are found in every low/hard state source (Fender 2001 and references therein). By analogy with AGN, it was already suggested that these properties could be explained by a compact, self-absorbed jet (Hjellming & Johnston 1988; Falcke & Biermann 1996, 1999; Fender 2001; see also Blandford & Königl 1979). Recently this interpretation has been confirmed by direct imaging of a milliarcsecond-scale jet from Cyg X-1 in the low/hard state (Fig 9.6

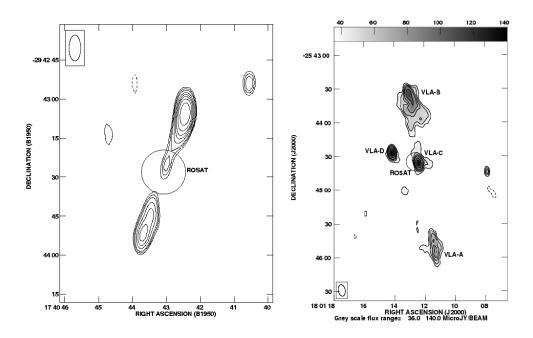


Fig. 9.7. Arcmin-scale radio jets from the galactic centre low/hard state sources 1E 1740.7-2942 and GRS 1758-258. Both of these systems spend nearly all their time in the low/hard X-ray state, therefore an interpretation of these lobes is that they result from the long-term action of steady jets on the ISM. From Mirabel et al. (1992) and Martí et al. (2002).

(left), Stirling et al. 2001); by analogy it is argued that all low/hard state sources are producing jets.

Furthermore, the hard 'plateau' state in GRS 1915+105, which has many similarities to the classical low/hard state, is also associated with a resolved milliarsec-scale jet (Dhawan, Mirabel & Rodríguez 2000; Fig 9.6 right panel), and the two galactic centre low/hard state sources 1E 1740.7-2942 & GRS 1758-258 are both associated with large-scale radio lobes, indicating the long-term action of a jet on the local ISM (Mirabel et al. 1992; Martí et al. 2002; Fig 9.7).

#### 9.4.1.1 Spectral extent and jet power

The radio spectrum in the low/hard state is 'flat' or 'inverted', in the sense that the spectral index  $\alpha \geq 0$ . This spectral component has been shown to extend to the mm regime for two low/hard state sources, Cyg X-1 and XTE J1118+480 (Fender et al. 2000b; Fender et al. 2001). In Fender (2001) it was suggested that

correlated radio–optical (and in fact X-ray) behaviour in the low/hard state transient V404 Cyg might suggest an extension of the jet spectral component to the infrared or optical bands. In fact in most, maybe all, low/hard state sources the optical flux densities seem to lie on a rather flat ( $\alpha \sim 0$ ) extension of the radio(–mm) spectrum (e.g. Brocksopp et al. 2001; Corbel et al. 2001). Jain et al. (2001) have observed a secondary maximum in the near-infrared light curve of XTE J1550-564 corresponding to a transition to the low/hard state, which they also attribute to synchrotron emission from a jet. Rapid optical variability from XTE J1118+480 in the low/hard X-ray state has also been interpreted as (cyclo-)synchrotron emission (Merloni, Di Matteo & Fabian 2000; see also Hynes et al. 2003) and may be associated with a sub-relativistic outflow (Kanbach et al. 2001; Spruit & Kanbach 2002).

Note that while admittedly not a canonical low/hard state source, there is unambiguous evidence for synchrotron emission from the jet source GRS 1915+195 extending at least to the near-infrared band (Fender et al. 1997; Mirabel et al. 1998; Eikenberry et al. 1998a, 2002; Fender & Pooley 1998, 2000). Furthermore, but not well explained, is the correlation in this source between infrared line strength and synchrotron continuum (Eikenberry et al. 1998b), indicating a coupling between thermal and nonthermal components. Qualitatively similar infrared flares have been observed from Cyg X-3 (e.g. Mason, Cordova & White 1986; Fender et al. 1996) which with the benefit of hindsight seem likely to be synchrotron in origin. Finally, Sams, Eckart & Sunyaev (1996) have observed extended infrared emission from GRS 1915+105 which they suggest originates in a jet (while possibly treated with some scepticism at the time, the observation of considerably larger X-ray jets from XTE J1550-564 makes a jet origin seem entirely plausible).

If the flat/inverted radio spectrum is due to self-absorbed synchrotron emission from a conical jet (Blandford & Königl 1979; Hjellming & Johnston 1988) then above some frequency (at which point the whole jet is optically thin) there should be a break to an optically thin spectrum with  $-1 \le \alpha \le 0$ . A compilation of observations of the low/hard state source GX 339-4 appears to have identified just such a cut off in the near-infrared (Corbel & Fender 2002).

How do we estimate the power associated with this steady, self-absorbed, synchrotron component? Without large amplitude variability, or directly resolved jets, it is not possible to associate a given luminosity with a certain volume, and it is not possible to directly apply standard 'minimum energy' arguments (as outlined in section 9.2). Therefore we must apply other arguments in order to estimate the total jet power. 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

$$P_{\rm J} \sim L_{\rm J} \eta^{-1} F(\Gamma, i) \tag{9.16}$$

where  $L_{\rm J}$  is the total radiative luminosity of the jet (i.e. the integral of  $L_{\nu}$  to the highest measured frequency),  $\eta$  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 2001).

Starting from the reasonable assumption that all the emission observed in the

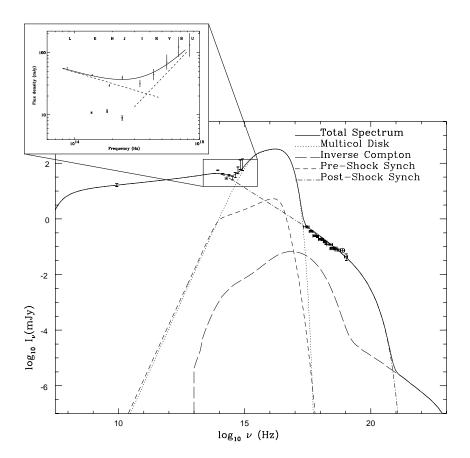


Fig. 9.8. Broadband jet-model fit to the radio—X-ray spectrum of GX 339-4 in the low/hard X-ray state (Markoff et al. 2003). The flat spectrum, self-absorbed, synchrotron component extends beyond the radio band and breaks to optically thin emission in the near-infrared (see insert, from Corbel & Fender 2002). An extrapolation of this near-infrared emission connects smoothly to the X-ray power law, suggesting that it may also be optically thin synchrotron emission, contrary to more widely-accepted Comptonisation models. The broadband spectrum and model fit are comparable to those for XTE J1118+480 while in the same X-ray state (Markoff, Falcke & Fender 2001).

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 (although it appears that the flat radio spectrum of Cyg X-1 extends at least as low as 350 MHz – de Bruyn, private communication), and while some low-frequency turnovers may 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.

Possibly the most comprehensive broadband spectrum compiled for a low/hard state source is that for the 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  $\mu$ m (Fender et al. 2001). In Fender et al. (2001) 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,  $\eta$ .

In Fender & Pooley (2000) an estimate of  $\eta$  was made for the radio 'oscillation' events from GRS 1915+105, and an upper limit of  $\eta \leq 0.15$  obtained. In the original model of Blandford & Königl (1979), it is likely that  $\eta \leq 0.15$ . In the model of Markoff, Falcke & Fender (2001; specifically for XTE J1118+480)  $\eta < 0.1$ . Finally it should be noted that Celotti & Ghisellini (2003) estimate  $\eta \leq 0.15$  for a sample of AGN. In reality, for the synchrotron process in jets it seems unlikely theoretically that  $\eta > 0.2$ , and this is backed up by no observational counter evidence. Therefore, for XTE J1118+480 the power in the jet is likely to be  $\geq 10\%$  of the X-ray luminosity. Since all low/hard state sources show a similar broadband spectrum (excluding the influence of different types of mass donor which only affects the near–infrared and optical bands) we're drawn to the conclusion that all low/hard state sources produce powerful jets (Fender 2001).

#### 9.4.1.2 Coupling to X-ray emission

A broad correlation between the radio and X-ray fluxes from a black hole binary in a low/hard state was first noted by Hannikainen et al. (1998) for GX 339-4. A similar correlation between radio and X-ray fluxes was found for Cyg X-1 (Brocksopp et al. 1999), and Fender (2001) suggested that the magnitude of the radio:X-ray flux ratio was similar for all low/hard state black holes.

In the past couple of years our understanding of this coupling between radio and X-ray emission has advanced significantly. Corbel et al. (2000, 2002), in a detailed long-term study of GX 339-4, has found that the radio emission in the low/hard state scales as  $L_{\rm radio} \propto L_{\rm X-ray}^b$  where  $b \sim 0.7$  for X-rays up to at least 20 keV (possibly steepening towards at linear relationship at the highest X-ray energies). This relation holds over more than three orders of magnitude in soft X-ray flux.

More recently Gallo, Fender & Pooley (2002, 2003) have found almost exactly the same coupling (in both normalisation and slope) over a comparable range in X-ray luminosity, for the low/hard state transient V404 Cyg. Furthermore, by compiling data for ten low/hard state sources, it was found that in the luminosity range  $10^{-5}L_{\rm Edd} \leq L_{\rm X} \leq 10^{-2}L_{\rm Edd}$  all systems are consistent with the same coupling with a very small scatter (less than one order of magnitude in radio flux), and that above a few % of  $L_{\rm Edd}$  the radio emission is rapidly 'quenched' (Gallo et al. 2003). Monte-Carlo simulations of Doppler-boosting effects indicate that such a small spread over such a large range in  $L_{\rm X}$  probably restricts the velocity of the jet in the low/hard

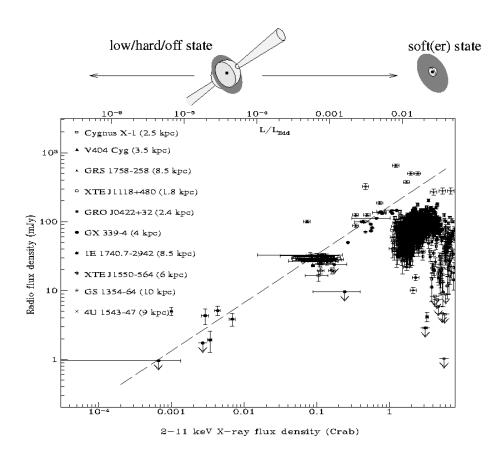


Fig. 9.9. (Quasi-)simultaneous radio and X-ray observations of black hole X-ray binaries, scaled to 1 kpc and corrected for absorption. Below a scaled X-ray flux of a few Crab (corresponding to  $\sim 1\%$  of the Eddington luminosity for a 10  $M_{\odot}$  black hole), all black hole binaries follow a correlation of the form  $S_{\rm radio} \propto S_{\rm X-ray}^{0.7}$ , in the 'low/hard' and 'off/quiescent' states. The relatively narrow distribution of data around a best-fit relation requires that the bulk Lorentz factor of jets in the 'low/hard' state  $\Gamma < 2$ . At higher luminosities in the (relatively rare) 'high/soft' state the radio emission is strongly suppressed. At still higher luminosities, X-ray transients (including recurrent sources such as Cyg X-3 and GRS 1915+105) produce repeated bright optically thin ejections. The hard 'plateau' state of GRS 1915+105 lies on an extension of the 'low/hard' state coupling. From Gallo, Fender & Pooley (2003); see also Corbel et al. (2001, 2003).

state to  $\beta = v/c \le 0.8$  (Gallo et al. 2003), unless the X-rays are also strongly beamed (in which case strong selection effects are at work).

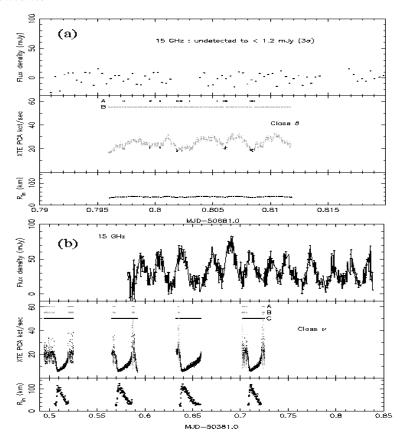


Fig. 9.10. GRS 1915+105 often cycles repeatedly between three X-ray states: A and B are disc-dominated and 'soft'; C is much harder (Belloni et al. 2000). Panel (a) above shows that when the source only exhibits soft states A and B, the radio emission is very weak; however when state C is present the radio emission is much stronger (and in fact there is a one-to-one correspondence between state C 'dips' and radio oscillation events). From Klein-Wolt et al. (2002).

## 9.4.1.3 Jets in 'quiescence'?

Outside of periods of transient outburst, BHCs are typically observed with luminosities in the range  $10^{-6}$ – $10^{-9}$  Eddington, and are considered to be 'quiescent' (e.g. Garcia et al. 2001). Their X-ray spectra are generally not distinguishable from the 'low/hard' state however, suggesting that they may also be associated with (relatively) powerful jets. In fact, V404 Cyg – the most luminous 'quiescent' black hole – is clearly associated with a relatively bright and variable radio source (e.g. Hjellming et al. 2000b) and GX 339-4 follows the radio – X-ray coupling discussed above down to comparable X-ray luminosities. In fact, combining the estimates of jet power in the low/hard state with the  $L_{\rm radio} \propto L_{\rm X-ray}^{0.7}$  relation indicates that 'quiescent' BHCs will in fact be 'jet-dominated', in the sense that most of the power output will be in the form of an outflow (Fender, Gallo & Jonker 2003). Combining this result with the greater 'radio loudness' of BHCs compared to NS X-ray binaries

can furthermore explain the discrepancy in their 'quiescent' X-ray luminosities (it is observed that NS transients are brighter X-ray sources in quiescence) without any significant advection of accretion power across a black hole event horizon (Fender, Gallo & Jonker 2003; see also Campana & Stella 2000; Garcia et al. 2001; Abramowicz, Kluzniak & Lasota 2002 and references therein for a broader discussion of this controversial issue).

## 9.4.2 Loss of jet in 'high/soft' states

The first indication that radio jets are not associated with 'soft' X-ray states can be traced back to Tananbaum et al. (1972), in which the appearance of the radio counterpart of Cyg X-1 was associated with a transition from the soft state back to the hard state (see also Hjellming, Gibson & Owen 1975). However, while it was surmised that changes in radio emission were associated with changes in the X-ray 'state' of X-ray binaries (Hjellming & Han 1995 and references therein), no clear pattern was established (except perhaps in Cyg X-3, where is has been realised for some years that periods of 'quenched' radio emission generally preceded large radio outbursts – e.g. Waltman et al. 1996).

The situation changed when GX 339-4 spent a year in the high/soft X-ray state in 1998. Radio monitoring of the source in the low/hard state prior to 1998 had already established the existence of a weak, mildly variable radio counterpart (Hannikainen et al. 1998), but throughout the soft state no radio counterpart was detected, despite multiple observations (Fender et al. 1999b). The source subsequently returned to the low/hard X-ray state and the weak radio counterpart reappeared (Corbel et al. 2000). Here was the strongest evidence that in 'soft' disc-dominated states the radio jet was either non-existent or more than an order of magnitude weaker.

Comprehensive radio and X-ray monitoring of Cyg X-1 has revealed that the suppression of the radio emission occurs rather rapidly once the transition to the high/soft state occurs at a bolometric luminosity of a few per cent Eddington (Gallo, Fender & Pooley 2003; Maccarone 2003). Given that there are no observed counter examples, we conclude that the soft X-ray state does is never associated with a strong radio jet. This assertion is supported by the detailed studies of GRS 1915+105 reported by Klein-Wolt et al. (2002), in which steady 'soft' X-ray states are never associated with bright radio emission (Fig 9.10).

#### 9.4.3 'Intermediate' and 'Very high' X-ray states

While the 'low/hard' and 'high/soft' X-ray states appear to represent both the most diametrically opposed and the most stable of accretion modes associated with black hole XRBs, there are also hybrid states. Both the 'intermediate' and 'very high' (see McClintock & Remillard in this book for more details) states are intermediate in their X-ray hardness between the two aformentioned canonical extremes. It has been suggested that they are the same state, in which case it is a curious fact that this state can occur over quite a large range in bolometric X-ray luminosity (see Homan et al. 2001).

Belloni (1998) suggested that the behaviour of GRS 1915+105, oscillating between relatively hard and (two) soft states (see also Belloni et al. 2000) was reminiscent of the 'very high' state as observed from other luminous X-ray transients. Since

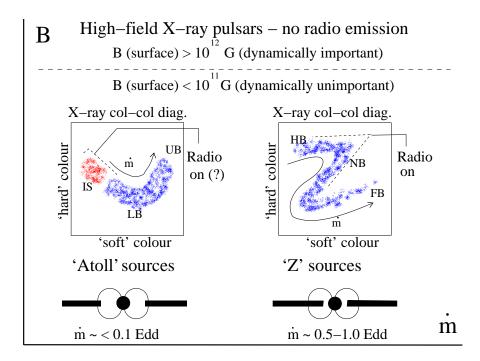


Fig. 9.11. Schematic illustrating our current understanding of the relation between radio emission and X-ray state for the persistent neutron star X-ray binaries

these oscillation events are unambiguously correlated with radio flaring (e.g. Pooley & Fender 1997; Mirabel et al. 1998; Klein-Wolt et al. 2002 – see Fig 9.10), a connection was made between this state and episodic jet production.

However, in a very important observation, Corbel et al. (2001) have shown that in a transition from the low/hard state to the intermediate state, the radio emission from XTE J1550-564 was reduced by a factor > 50. Furthermore, the state in which the jet from Cyg X-1 is suppressed (see Fig 9.9) may not be the canonical 'high/soft' state, but the 'intermediate' state (e.g. Belloni et al. 1996; Miller et al. 2002a, but see Gierlinski et al. 1999). What remains clear is that when the X-ray spectrum softens the jet is suppressed. What needs further investigation is the exact evolution of the X-ray spectral and jet parameters as this suppression occur, since at present the most comprehensive studies (e.g. Corbel et al. 2003; Gallo et al. 2003) are based only on X-ray flux, not spectral, evolution. In a related work, Pottschmidt et al. (2000) report that the magnitude of X-ray time lags in Cyg X-1 is much greater during transitions than either before or after, and suggest that this effect may be related to the formation of outflows at these times.

## 9.4.4 The highest luminosities and X-ray transients

X-ray transients typically peak at luminosities greater than those which generally characterise the 'high/soft' state, although often still sub-Eddington (Chen, Shrader & Livio 1997). Such high luminosities are, in nearly all cases, very short lived (typically days or less) and the 'state' is considerably more difficult to characterise than the canonical 'low/hard' or 'high/soft' states.

It was already known since the 1970s that bright X-ray transients were associated with transient production of radio emission, whose characteristics could be described at a basic level by 'synchrotron bubble' models (Hjellming & Han 1995 and references therein, and also section 9.2.3). In several, perhaps all, cases, there is evidence for multiple ejection events (e.g. Harmon et al. 1995; Kuulkers et al. 1999; Brocksopp et al. 2001). The clearest difference with low/hard state steady jets is the rapid evolution to an optically thin spectrum ( $\alpha \sim -0.6$ ) and monotonic decay (Fender 2001). In addition, linear polarisations of up to a few ×10% have been measured (e.g. Fender et al. 1999a; Hannikainen et al. 2000), and also circular polarisation at the  $\sim 1\%$  level (see section 9.2.6). The broad properties of these transient radio events – ie. the spectral evolution and a tendency for multiple ejection events – seem to be similar whether the events are 'rare' (e.g. A0620-00, GS 1124-68) or 'frequent' (e.g. Cyg X-3, GRS 1915+105).

These ejection events appear to be associated with the change in X-ray state between 'off' (which may be analogous to 'low/hard') and very bright 'high/soft' or 'very high' states (e.g. Harmon et al. 1995; Fender & Kuulkers 2001). Some transients actually seem only transit to bright 'low/hard' states and may (e.g. V404 Cyg) or may not (e.g. XTE J1118+480) also display bright optically thin events. One source seems to sit persistently at close to Eddington luminosities, and is a spectacular source of relativistic jets: GRS 1915+105. This source exhibits a wide range of X-ray properties, none of which can be easily classified as normal 'low/hard' or 'high/soft' states (Belloni et al. 2000). Its overall X-ray properties may be reminiscent of the 'very high state' (Belloni 1998), but the erratic flips between hard and (two sorts of) soft states is rather unlike any other X-ray binary. However, GRS 1915+105 does fit into the general pattern associating 'hard' X-ray states with jet formation, at least for the 'plateau' and 'oscillation' events (Dhawan et al. 2000; Klein-Wolt et al. 2002). Mirabel et al. (1998) have suggested that a brief X-ray spike, during which the source X-ray spectrum softens considerably, may indicate the 'launch moment' of the jet - this would clearly be an important discovery if true and merits further attention. Cyg X-3 may be displaying similar behaviour to GRS 1915+105 – it is certainly accreting at a very high level and almost continuously producing jets – but details of its workings are hidden in the dense wind of its Wolf-Rayet companion.

These radio flares (see section 9.2.3) have by now been clearly and repeatedly associated with highly relativistic bulks motions (section 9.2.4). In a comparison of peak radio and X-ray emission from transients, Fender & Kuulkers (2001) found that there appears to be nothing special about the sources in which relativistic jets had been resolved. Therefore it seems reasonable to assume (Occam's razor) that the initial radio emission associated with X-ray transients is always associated with a relativistic outflow. Note also that Garcia et al. (2003) have suggested that the

largest-scale resolved radio jets may be associated with X-ray transients with the relatively long orbital periods.

## 9.5 Disc-jet coupling in neutron star binaries

As noted in the introduction, radio emission seems to be associated with both 'Z' and 'atoll' type neutron star X-ray binaries, but not with the high-field X-ray pulsars. See Fig 9.11 for a summary of our current understanding. It is interesting as a historical note that a predictable coupling between X-ray 'state' and radio emission was first suggested for the Z sources (see below), but that in recent years nearly all the attention has switched to the analogous coupling in black hole systems.

#### 9.5.1 'Z' sources

The prototype Z source, Sco X-1, has been known as a variable radio source since the early 1970s (Hjellming & Wade 1971b). This source, together with GX 5-1, GX 17+2, GX 349+2, GX 340+0 and Cyg X-2 form a group of neutron star X-ray binaries accreting at or near to the Eddington limit and exhibiting clear patterns of spectral and timing behaviour (Hasinger & van der Klis 1989). It is ironic that an initial association with large-scale radio lobes was disproved by the same proper motion studies (Fomalont & Geldzahler 1991) which subsequently discovered highly-relativistic jets on milliarcsecond scales (Bradshaw, Fomalont & Geldzahler 1999; Fomalont et al. 2001a,b). The other five Z sources also have radio counterparts with comparable luminosities (Penninx 1989; Hjellming & Han 1995; Fender & Hendry 2000).

Priedhorsky et al. (1986) first suggested that an empirical coupling between X-ray and radio (and optical) emission existed for Sco X-1. Penninx et al. (1988) confirmed and refined this pattern of behaviour for GX 17+2 and Penninx (1989) suggested that all Z sources would display comparable behaviour. The same pattern of behaviour has been established for Cyg X-2 (Hjellming et al. 1990a) but apparently not in GX 5-1 (Tan et al. 1991; but see below for a possible explanation). The radio behaviour seems to correlate with position in the 'Z'-shaped track traced out on timescales of hours to days in the X-ray colour-colour diagram (see Fig 9.11) in the sense that it is strongest on the 'horizontal branch' and weakest on the 'flaring branch', revealing an apparent anti-correlation with mass accretion rate as in the black holes.

As noted above, intensive VLBI campaigns on Sco X-1 have revealed the presence of a relativistic outflow (Bradshaw et al. 1999; Fomalont et al. 2001a,b – see Fig 9.12). In particular, it seems that following core radio flaring, relativistic ( $\Gamma \geq 2$ ) beams are acting on radio knots which themselves propagate away from the binary core with mildly relativistic velocities. Given the similarity of the radio properties between the six Z source, we can fairly confidently conclude that they all have jets – however, since the brightest component is the core, it cannot yet be asserted that the jet-knot interaction is occurring in all of them. Furthermore, caution should be exercised in attempting to associate unresolved radio monitoring (e.g. that performed in the 1990s with the Green Bank Interferometer) with X-ray events (but see Hjellming et al. 1990b for a successful experiment) since the delay between core events and subsequent brightening in the knots is comparable to the timescale of motion in the

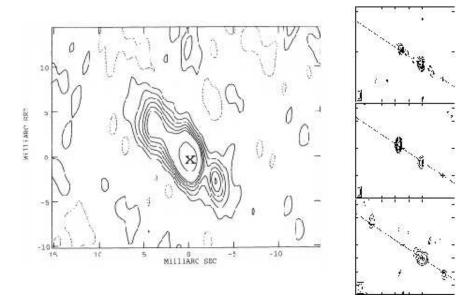


Fig. 9.12. (Left:) A VLBA image of milliarcsecond-scale radio jets from Sco X-1 with the core indicated by a 'X'. (from Bradshaw, Fomalont & Geldzahler 1997). (Right:) Multiple sequences of such observations reveal movement of the radio lobes at mildly relativistic velocities ( $\sim 0.4c$ ) while being sporadically energised by a much more relativistic ( $\Gamma \geq 2$ ) beam from the core (adapted from Fomalont et al. (2001a,b)).

Z – this may be an explanation for the 'anomalous' observations of GX 5-1 by Tan et al. (1991).

At present there is little study of, and consequently little evidence for, possible extensions of the jet spectrum beyond the radio band in the Z sources (although there are hints of some correlated optical behaviour). Estimates of the power in the jets are rather uncertain (Fomalont et al. 2001b estimate super-Eddington power in the jets of Sco X-1, but this is based upon the assumption that the major cooling process is synchrotron losses, which is far from being clear), and are at present based solely upon radio variability.

## 9.5.2 'Atoll' sources

It is worth re-stressing here that I am adopting a definition of 'atoll' source to mean all non-Z low magnetic field accreting neutron stars – this is considerably broader than the original definition of Hasinger & van der Klis (1989). Adopting this loose definition, atoll sources are the single largest class of X-ray binary, contributing around 45% of the currently known population (in this classification, 'atoll' includes 'bursters', 'dippers' etc). Investigation of their disc-jet coupling, if any, is therefore of paramount interest – not least because they can exhibit 'hard' X-ray states which are very similar to the 'low/hard' states of BHCs, while they of course remain fundamentally different in possessing a solid surface.

Hjellming & Han (1995) list the small number of reported radio detections of

atoll sources known at that time – beyond some weak detections of globular cluster sources, only GX 13+1 was repeatedly detected at a relatively strong level (Garcia et al. 1988) – in fact at about the same radio luminosity as the Z sources (Fender & Hendry 2000). However, GX 13+1 seems to be far from a 'normal' atoll source (Homan et al. 1998; Schnerr et al. 2003). It is interesting to note that the three other brightest atoll sources, GX 3+1, GX 9+1 and GX 9+9 have never been detected in the radio band, and spend most of their time in the soft 'upper banana' (UB in Fig 9.11) state.

Most other atoll sources show somewhat harder spectra associated with the 'lower banana' (LB) or 'island' (IS) X-ray states (which are similar to the black hole 'low hard' state). Amongst these, Martí et al. (1998) reported repeated detections of the atoll source 4U 1728-34 (GX 354-0) at a level of up to  $\sim 0.6$  mJy. In recent simultaneous radio and X-ray observations of the same source, Migliari et al. (2003) have revealed clear correlations between X-ray luminosity and power spectral properties with the radio flux, establishing for the first time a disc–jet coupling in such systems. Despite their relative faintness in the radio band, it seems that there is a rich phenomenology to be explored in these 'hard' atoll sources.

#### 9.5.2.1 Neutron star transients

There are a few detections of radio emission associated with neutron star X-ray transients (see Fender & Kuulkers 2001 for a list). These include an unusual assortment of objects: the recurrent transient Aql X-1 (Hjellming, Han & Roussel-Dupre 1990), the first accretion-powered msec pulsar SAX J1808.4-3658 (Gaensler, Stappers & Getts 1999) and 4U 1730-335 ('The Rapid Burster', Moore et al. 2000). To hammer home a point made earlier, this author considers all these sources to be quite similar in that they are low magnetic field neutron stars accreting, on average, at a considerably sub-Eddington rate, and I call them all 'atoll' sources (it interesting to note that there has not yet been a NS transient which displayed Z-type properties even at the peak of outburst). The sample for NS transients is considerably poorer than that for BH transients, something which can be at least partially attributed to the fact that they are in general fainter in the radio band (Fender & Kuulkers 2001; see section 9.5.3).

Cir X-1 can be considered as a recurrent neutron star transient (perhaps comparable to GRS 1915+105 and Cyg X-3 in this respect); it undergoes radio and X-ray flares every 16.6-days, during which periods its X-ray luminosity is super-Eddington. This periodicity is interpreted as heightened accretion during periastron passage of the neutron star in a highly elliptical orbit – essentially this system undergoes repeated, periodic, soft X-ray transient outbursts. The system is associated with an arcsec-scale one-sided radio jet (Fender et al. 1998) embedded within an arcminute-scale radio nebula (Stewart et al. 1993). The X-ray classification of Cir X-1 has alternated between 'Z' and 'Atoll' types, and at present it is not clear to which category it belongs.

#### 9.5.3 Black holes versus neutron stars

There are clearly some broad similarities between black holes and neutron stars in their X-ray : radio coupling. These include:

- An association between states with hard X-ray spectra and strong X-ray variability and the presence of radio emission
- An association between bright X-ray outbursts and radio flare events
- In the brightest cases, the formation of large-scale radio lobes in the ISM

Are there differences between jets from neutron stars and those from black holes? There is at least one. Fender & Kuulkers (2001) have found that defining a quantity 'radio loudness' as the peak radio flux of transients (in mJy), divided by their peak X-ray flux (in Crab), black hole transients are more radio loud than neutron stars (Fig 9.13). Furthermore, by comparing the data for low/hard state black holes and neutron star 'Z' sources presented in Fender & Hendry (2000) they found a similar difference. In both classes of object black holes seem to be about one or two orders of magnitude more radio loud than neutron star systems. Migliari et al. (2003) confirm a difference in radio luminosity by a factor  $\sim 30$  between the atoll source 4U 1728-34 in a hard state and low/hard state black holes at a comparable Eddington ratio. This difference may be due to greater photon (Compton) cooling of shocked electrons in the neutron star systems, due to the presence of a radiating surface or low-level magnetic field, or perhaps due to some extra source of power in the black hole systems (Fender & Kuulkers 2001). A further possibility (Heinz & Sunyaev 2003; Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2003) is that the radio loudness scales with mass. However in this case, assuming the 'stellar mass' black holes are on average five times more massive than the neutron stars, this suggests a rather steeper dependence on mass than considered by these authors.

#### 9.6 High energy / particle emission from jets

Observations in the past two or three years have revealed unambiguously that jets may be not only *associated* with phases of high energy emission, but may actually be the *sites* of origin of the observed emission.

#### 9.6.1 X-rays

The possibility of some of the X-ray emission from X-ray binaries arising in jets has already been alluded to in this text, and explicitly suggested in the literature (e.g. Markoff, Falcke & Fender 2001; Vadawale, Rao & Chakrabarti 2001; Markoff et al. 2003; see also Atoyan & Aharonian 1999; Miller et al. 2002b). Before discussing this further, it is worth restating the fact that in the past three years *Chandra* imaging has unambiguously associated both thermal / emission line (Migliari, Fender & Mèndez 2002) and 'hard' X-ray spectra (Corbel et al. 2002; see also Angelini & White 2003) with jets from X-ray binaries (Fig 9.14).

In a detailed model, Markoff et al. (2001, 2003; see Fig 9.8 and also Falcke & Biermann 1996, 1999) have suggested that the X-ray power law observed in the low/hard X-ray state may in fact be the optically thin synchrotron emission from the jet which is self-absorbed at lower frequencies. In fact as already noted a break from optically thick to optically thin emission from the jet seems to have been found in the right place for GX 339-4 (Corbel & Fender 2002 – in fact this may have already been noted by Motch et al. 1985). This is a radically different interpretation for the origin of X-rays in this state, which are generally ascribed to thermal Comptonisation

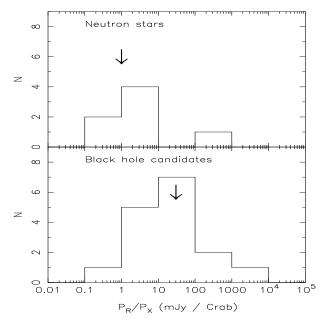


Fig. 9.13. Histograms of the 'radio loudness' of neutron star (top) and black hole (bottom) transients. The black holes are significantly more 'radio loud' than the neutron stars, by one to two orders of magnitude. Also indicated by arrows are the mean 'radio loudnesses' of the neutron star Z sources and the brighter low/hard state black holes, revealing the same trend. From Fender & Kuulkers (2001).

(e.g. Poutanen 1998 and references therein; for more detailed objections to the model of Markoff et al. see Zdziarski et al. 2003). The implication of the model, if correct, would be that the majority of power output in the low/hard state is in the form of a jet. Note that in this model the X-ray emitting region would be spatially unresolvable and it is not therefore an explanation for the extended X-ray jets observed from XTE J1550-564 and SS 433 (Fig 9.14). Vadawale, Rao & Chakrabarti (2001) have suggested that some component of the X-ray spectrum of GRS 1915+105 may arise in synchrotron emission. Georgonapoulos, Aharonian & Kirk (2002) have suggested that X-ray emission may originate due to Comptonisation by jet electrons of photons from the companion star.

Returning to the large-scale X-ray jets, the fact that three have been clearly imaged in the past  $\sim 2.5$  years with Chandra (Marshall et al. 2002; Migliari et al. 2002; Corbel et al. 2002; Angelini & White 2003) indicates that they are likely to be rather ubiquitous. The fact that X-ray emission, with a spectrum more or less indistinguishable from the 'off' state (for XTE J1550-564 and 4U 1755-33) may be associated with beamed, long-lasting, jets is of considerable interest. It certainly shows that jets, almost certainly via internal or external shocks, may mimic faint hard states up to several years after the binary source may have completely turned off. These are all extra concerns for interpretations of the 'quiescent' luminosities of transient X-ray binaries: the X-ray jets of XTE J1550-564 (Corbel et al. 2002; Kaaret

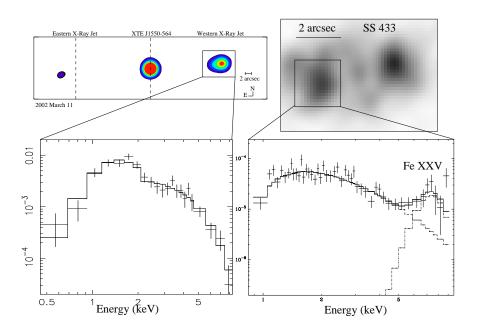


Fig. 9.14. Spatially resolved X-ray spectra of X-ray jets from the black hole transient XTE J1550-564 (left) and the persistent powerful jet source SS 433 (right). Note the strong emission line (probably Fe XXV) in the SS 433 spectrum, which is clearly not present in the jets of XTE J1550-564. Observations such as these demonstrate unequivocally that jets from X-ray binaries can be sources of both line-rich ('thermal') and featureless ('nonthermal') X-ray spectra which may be beamed. Adapted from Corbel et al. (2002), Kaaret et al. (2003), Migliari et al. (2002).

et al. 2003; Tomsick et al. 2003) are more luminous than most of the 'quiescent' X-ray luminosities for black holes reported in Garcia et al. (2001).

## 9.6.2 High-energy / particle emission

In an important recent work, Paredes et al. (2000; see also Ribó et al. 2002 and Paredes et al. 2002) have reported a convincing association between a massive X-ray binary with persistent radio jets and an unidentified EGRET gammaray source. Their favoured scenario is that relativistic electrons in the jet Comptonise photons from the binary companion (similar to the model of Georgonapoulous et al. 2002). The massive binary and probable jet source LS I +61 303 (Strickman et al. 1998; Gregory & Neish 2002 and references therein) may also be associated with a gamma-ray source, with a similar physical origin a possibility.

Heinz & Sunyaev (2002) have discussed the possible contribution of X-ray binary jets to the production of galactic cosmic rays. They conclude that, while in terms

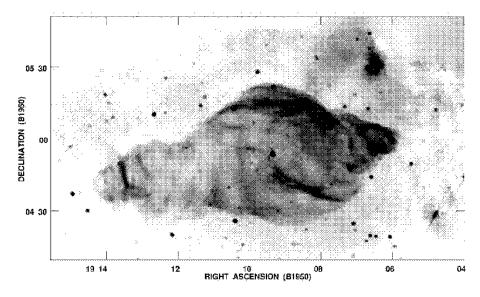


Fig. 9.15. The W50 nebula surrounding the powerful, quasi-continuous jet source SS 433, which seems to have been distorted by the action of the jets over thousands of years. From Dubner et al. (1998).

of overall energetics such jets are still likely to inject less power into the ISM than supernovae, they may contribute a specific and detectable component to the cosmic ray spectrum. In particular, the shocks in the ISM associated with jets from X-ray binaries will be considerably more relativistic than those associated with the supernovae, and thus may be considerably more efficient at particle acceleration.

Di Stefano et al. (2002) have suggested that jets from X-ray binaries could be detectable sources of high-energy neutrinos. Kaiser & Hannikainen (2002) have further suggested that X-ray binary jets may be the origin of a putative redshifted 511 keV annihilation line observed from the direction of the X-ray transient GRS 1124-684 (however, an alternative explanation which is perhaps more widely accepted is that the  $\gamma$ -ray emission was associated with a transition of  $^7\mathrm{Li}$  – Martin et al. 1994). A possible explanation for the  $^7\mathrm{Li}$  production is spallation in the companion star atmosphere due to the collision of a misaligned jet (Butt, Maccarone & Prantzos 2003).

In the light of the possibility of X-rays directly from jets, several authors have considered the possibility of 'micro-blazars' in which jets aligned close to the line of sight could be observed as  $\gamma$ -ray sources (e.g. Mirabel & Rodriguez 1999; Kaufman Bernado et al. 2002; Romero et al. 2002).

## 9.7 Interactions

As has already been alluded to in previous sections, it is becoming clear that interactions between the jet, as launched by the combination of accretion flow plus compact object, and the ambient medium need to be taken into account for a full understanding both of the radiation we observe and the internal physics of 9.7 Interactions 33

the outflows. Of the classes of radio-emitting X-ray binaries only the weakest, the atoll sources, have yet to provide us with a direct example of jet-ISM interactions. These interactions have the potential to act as independent measures of the power associated with jets from X-ray binaries ('calorimeters'), although it has been argued that they may be harder to detect than the corresponding lobes associated with AGN (Heinz 2002; see also Levinson & Blandford 1996). Furthermore, as with AGN, it is possible that some of the presumed shock acceleration may result not from jet-ISM interactions but from internal shocks (Kaiser, Sunyaev & Spruit 2000), perhaps resulting from varying flow speeds (see also discussion in Migliari et al. 2002 for SS 433).

Considering first the black hole low/hard state sources, as well as the milliarcsec-scale jet from Cyg X-1 (Stirling et al. 2001; Fig 9.6), arcmin-scale (≡ parsec-scale) jets have been observed from 1E 1740-2942 and GRS 1758-258 (Mirabel et al. 1992; Martí et al. 2002; see Fig 9.7). It seems clear that these larger lobes are the result of in-situ particle acceleration at the interface between the steady jets and the ISM.

Observations of large-scale radio and X-ray jets from the black hole transient XTE J1550-564 (Corbel et al. 2002; Kaaret et al. 2003; Tomsick et al. 2003) have provided us with unambiguous evidence of broadband particle acceleration at the same time as the jet is decelerating (Figs ??). Similarly, a one-sided highly relativistic jet from Cyg X-3 on mas-scales (Mioduszewski et al. 2001) seems to become a slower-moving, two-sided jet on arcsec-scales (Martí, Paredes & Peracaula 2001), indicating a deceleration and in-situ particle acceleration.

In the prototype of the Z sources, the brightest 'persistent' neutron stars, Sco X-1, Fomalont et al. (2001a,b) have found evidence for the action of an unseen, highly relativistic flow, on radio-emitting clouds which are themselves moving away from the binary core at mildly relativistic velocities. The recurrent neutron-star transient Cir X-1 is associated not only with an asymmetric arcsec-scale radio jet but with an arcmin-scale radio nebula (Stewart et al. 1993; Fender et al. 1998) which, given the observed rapid timescale of radio variability from this source, can be unambiguously associated with in-situ particle acceleration, almost certainly powered by the jet. The nebula around Cir X-1 provides a good example of the use of such interaction zones as calorimeters – a simple 'minimum energy' estimate indicates a total energy in the synchrotron emitting plasma of  $> 10^{48}$  erg, corresponding to, for example, three thousands years' action at 1% of the Eddington luminosity (see Heinz 2002 for further discussion).

Most spectacularly, the persistent powerful binary jet source SS 433 powers the degree-scale W50 radio nebula (Fig 9.15), within which are also located similar-scale X-ray jets (Brinkmann, Aschenbach & Kawai 1996). Note that on smaller arcsec scales there is already evidence for reheating (Migliari et al. 2002), revealing that particle re-acceleration is not only present, but occurs repeatedly at different points in the flow.

In many, perhaps all, of these sources it now seems clear that a picture of a single finite phase of particle acceleration following by monotonic fading as the source expands and propagates away from its launch site is far too simplistic. Multiple phases of particle accelerations due to shocks – whether internal or external – are perhaps instead the norm. While this necessarily complicates our understanding of

the disc—jet coupling (particularly when the various physically distinct sites cannot be spatially resolved), it does, on the other hand, allow us to constrain the power of jets in radio-quiet phases such as the 'high/soft' state. This follows because if these states were producing powerful jets which for some reason (e.g. extreme Compton cooling) were not radio-loud initially, we would still expect the signatures of subsequent shock accelerations to be found.

## 9.8 Relation to other jet sources

It is a common and useful exercise to compare accretion in X-ray binaries with the analogous processes in related systems, most commonly Cataclysmic Variables (CVs; see Kuulkers et al. this volume). In the following I shall briefly compare X-ray binaries to other jet-producing systems. Fig 9.16 indicates schematically possible similarities and differences between jet formation in some of these different classes of object.

#### 9.8.1 Active Galactic Nuclei

The name 'microquasar' (Mirabel et al. 1992) clearly reflects the phenomenological similarities between jet-producing X-ray binaries and Active Galactic Nuclei (AGN). Detailed quantitative comparisons are only just beginning to be made; and will no doubt be the subject of many future research papers. At the very roughest level, it is tempting to associate the (disputed) 'radio loud' and 'radio quiet' dichotomy observed in AGN with jet-producing (hard and transient) and non-jet-producing (soft) states in X-ray binaries (see e.g. Maccarone, Gallo & Fender 2003). Furthermore perhaps FRI jet sources can be associated with the low/hard state and FRIIs with transients. Meier (1999; 2001) has considered jet production mechanisms in both classes of object, and drawn interesting parallels. Gallo, Fender & Pooley (2003; amongst others!) have made a qualitative comparison between FRIs and low/hard state black hole X-ray binaries and FRIIs and transients.

It is interesting to note that the short timescale disc-jet coupling observed in GRS 1915+105 (Pooley & Fender 1997; Eikenberry et al. 1998; Mirabel et al. 1998; Klein-Wolt et al. 2001), in its most basic sense – that radio events are preceded by a 'dip' and associated spectral hardening in the X-ray light curve – may also have an analog in AGN: Marscher et al. (2002) have reported qualitatively similar behaviour in 3C 120.

Perhaps most exciting is the recent discovery that the power-law relation between radio and X-ray luminosities found for low/hard state BHCs (Corbel et al. 2001, 2003; Gallo, Fender & Pooley 2003; see Fig 9.9) may be directly relevant for the disc-jet coupling in AGN. Merloni, Heinz & di Matteo (2003) and Falcke, Körding & Markoff (2003) have both reported a 'fundamental plane' of black hole activity resulting from the coupling between mass, jet power and accretion power. This plane matches almost perfectly with the Gallo, Fender & Pooley (2003) relation once the mass term is taken into account, indicating truly similar physics across six to seven orders of magnitude in mass.

## 9.8.2 Gamma ray bursts

While currently observations allow that X-ray binary jets may achieve on occasion bulk Lorentz factors as large as those of the fastest AGN jets (Fender 2003), Gamma ray bursts (GRBs) appear to belong to another regime, with  $\Gamma > 100$  (e.g. Baring & Harding 1997; Lithwick & Sari, 2001). While the physics of jet interaction and emission may be similar, being based upon shock acceleration and the synchrotron process, the workings of the jet-producing engine in GRBs are so buried that it is hard to know how to make quantitative comparisons. Nevertheless, such comparisons should be attempted, and the differences between XRB transients, some of which reach super-Eddington rates, and GRBs, may not be as great as currently thought. Since in X-ray binaries we are fairly confident that to some degree the jet activity reflects that in the accretion flow, it may be conceivable that the (highly compressed) patterns of behaviour in GRBs (originating in the jet) may reveal similarities with the slower black hole accretion processes observed in XRBs.

#### 9.8.3 Other galactic jet sources

X-ray binaries aside, there are multiple other sources of jets associated with 'stellar'-scale objects within our galaxy (and presumably others). However, in no other class of sources are there truly relativistic jets associated with accretion.

There are however nonrelativistic jets associated with accretion in (at least) Young Stellar Objects (YSOs; e.g. Lada 1985; Reipurth & Bally 2001) and Super Soft Sources (SSS; see Kahabka in this volume for a full description). The SSS can perhaps be most clearly compared to the X-ray binaries since they seem to be producing highly collimated jets as a result of high accretion rates in a binary (Cowley et al. 1998 and references therein), albeit at much lower velocities (0.01c or less). These jets are revealed not by their radio emission but by optical twin optical/infrared lines originating from the jets (reminiscent of SS 433). The 'symbiotic' binary CH Cyg is another interesting source of sub-relativistic jets associated with accretion. These jets do emit in the radio band, and may be precessing (Crocker et al. 2002); furthermore Sokoloski & Kenyon (2003) have reported a possible disc-jet coupling similar to that found in GRS 1915+105. Finally it is often noted that radio pulsars such as the Crab and Vela seem to be associated with (relativistic) jets and yet are not accreting (e.g. Blandford 2002).

One conclusion has been drawn from the comparison of X-ray binaries with such diverse galactic objects: that the jet velocity is always comparable to the escape velocity of the accreting object (e.g. Livio 1999; Mirabel & Rodríguez 1999). While this seems to hold over the sub-relativistic and mildly-relativistic regime, evidence for varying jet speeds from the same black hole, and for  $\Gamma > 2$  flows from neutron stars seem to indicate that it is not a hypothesis which can be extrapolated beyond neutron stars.

#### 9.8.4 Ultraluminous X-ray sources

Ultraluminous X-ray sources are X-ray sources in external galaxies with apparent isotropic luminosities requiring black hole masses of  $\sim 100 M_{\odot}$  or more in order to remain sub-Eddington (i.e. at least a factor of a few more luminous that GRS 1915+105). There are at present three competing explanations for these

sources, all involving accretion onto a black hole. If the radiation really is isotropic then 'intermediate mass black holes' are invoked (e.g. Colbert & Mushotzky 1999); alternatively the radiation may be anisotropically emitted from the accreting region (King et al. 2001) or relativistically aberrated due to e.g. an origin in a jet (Körding, Falcke & Markoff 2002; see also Georganopoulos et al. 2002). At the moment the nature of ULXs remains unclear (see more detailed discussion by King, this volume).

An obvious prediction of the jet model would be radio counterparts to such sources, and there is tantalising evidence that this may have recently been achieved. Dubus & Rutledge (2002) have suggested that the X-ray source M33 X-8 may be associated with a weak radio source; Kaaret et al. (2003) claim to have identified the radio counterpart to an ULX in NGC 5408. While these claims need confirmation, observations of the radio counterparts of such sources will surely provide strong clues to their intrinsic nature.

## 9.9 On the origin of jets

In this review the observational properties of jets from X-ray binaries have been considered and some broad-ranging empirical relations have been established (most notably the association of jets with 'hard' X-ray states). Such empirical connections require theoretical interpretation and the theory community has in recent years begun to rise to the task (motivated at least in part by a desire to use X-ray binary jets to explain those of AGN). There is certainly no room here to discuss these theoretical developments in detail, but it is worth pointing out some key relevant works.

Blandford & Payne (1982; see also e.g. Ogilvie & Livio 2001) provided the groundwork for models in which magnetic fields rooted in an accretion flow may produce 'radio' jets. The association of the 'low/hard' state with ~steady jet formation has been interpreted by Meier (2001) and Meier, Koide & Uchida (2001) as strong evidence for MHD jet formation. In this scenario the strongest jets result from accretion flows with a large scale height, and so the jets are naturally suppressed in 'high/soft' accretion states which are dominated by a geometrically thin accretion disc. Merloni & Fabian (2002) discuss 'coronal outflow dominated accretion discs' in which they balance both accretion and outflow powers. Livio, Pringle & King (2003) have put forward a model in which the hard X-ray states of BHCs represent modes in which the bulk of the accretion energy is deposited into the bulk flow of a relativistic jet. Such 'jet dominated' states may be empirically borne out by observations (Fender, Gallo & Jonker 2003). Lynden-Bell (2003) discusses the formation by magnetised accretion discs of 'towers' which can collimate jets. In all these theoretical models a magnetised accretion flow is the basis of a MHD outflow; given the widespread acceptance of the magneto-rotational instability (MRI) as the origin of accretion disc viscosity (e.g. Balbus & Hawley 1991; Turner, Stone & Sano 2002) this highlights the probably key role of magnetic fields in the coupled accretion – outflow system (see e.g. Kudoh, Matsumoto & Shibata 2002 for a discussion of a possible relation between MRI and jet formation). Fig 9.16 presents four different configurations of accretion with magnetic fields which may result in jet formation. In a rather different but still magnetically-orientated approach Tagger & Pellat (1999; see also e.g. Varniere & Tagger 2002), in the 'accretion-ejection instability' model have suggested

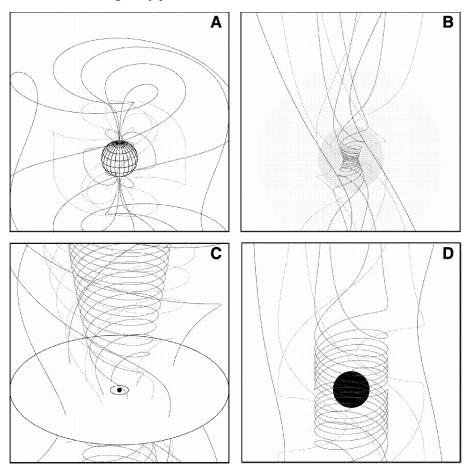


Fig. 9.16. Four ways to make jets with magnetic fields. **A:** dipole field of a rotating neutron star. **B:** A collapsing object drawing and winding up an initially uniform field. **C:** Poloidal magnetic field from a magnetised accretion disc. **D:** Framedragging near a rotating black hole resulting in strong coiling of the magnetic field lines. Types **C** and **D**, although possibly also **A** may be relevant for X-ray binaries; type **A** for isolated pulsars; types **C** and **D** for AGN, and types **B**, **C** or **D** may be relevant for gamma ray bursts. From Meier, Koide & Uchida (2001).

that an instability related to the vertical component of magnetic field in the inner regions of accretion discs may result in the transport of energy and angular momentum away from the accretion flow, possibly powering a jet or wind. In this, and the related works of Das, Rao & Vadawale (2003) and Nobili (2003), the jet should be intimately coupling to the timing properties of the accretor (of course this is already empirically observed to a certain extent since the different states of both BHCs and NS X-ray binaries have different timing properties).

As an alternative to magnetic acceleration, radiative acceleration (e.g. the 'Compton Rocket' of O'Dell 1981) is unlikely to be able to push jets to the highest observed

bulk velocities (Phinney 1982) but may still be operating, via line-locking, in the case of SS 433 (Shapiro, Milgrom & Rees 1986).

Many variants on radiatively inefficient accretion flows are now beginning to consider outflows as part of their solutions (e.g. Narayan & Yi 1995; Blandford & Begelman 1999; Das 1999; Beckert 2000; Markoff et al. 2001; Becker, Subramanian & Kazanas 2001). It remains to be seen which, if any, of these models comes closest to reproducing the observational characteristics of accretion onto black holes at a variety of rates, but note that numerical simulations of radiatively inefficient accretion flows also seem to form jets and outflows (Hawley & Balbus 2002). In fact already more than two decades ago Rees et al. (1982) discussed a likely connection between 'ion-supported tori' (essentially advective flows) and the formation of radio jets. While Rees et al. (1982) were motivated by the study of AGN, they noted that '..relativistic jets collimated by tori around stellar-mass black holes may exist within our Galaxy.'.

Are we ever going to be able to directly image the jet formation region in X-ray binaries? It seems unlikely – Junor, Biretta & Livio (1999) report the direct imaging of jet formation around the (low-luminosity) AGN M87 at a distance of  $\sim 100$  Schwarzschild radii from the black hole. Comparing M87 to X-ray binaries in our own galaxy, the ratio of distances is so much smaller than the ratio of black hole masses (and therefore Schwarzshild radii), that such imaging will not be possible. For example, a structure of size 100 Schwarschild radii around a  $10M_{\odot}$  black hole at a distance of 5 kpc would have an angular size of  $\sim 10^{-11}$  arcsec! Therefore the key to studying jet formation in X-ray binaries will remain in careful multiwavelength studies at the highest time resolution, such as those performed with such success on GRS 1915+105 (e.g. Mirabel et al. 1998; Klein-Wolt et al. 2002).

#### 9.9.1 On black hole spin

It has been suggested both for AGN and for XRBs that the jets may in whole or in part be powered by the spin of the black hole (e.g. Blandford & Znajek 1977; Koide et al. 2002), although Livio, Ogilvie & Pringle (1999) argue that the energy extracted from the black hole in this way will never exceed that from the inner regions of the accretion disc. For the black holes in the low/hard state the apparently tight and universal correlation between X-ray and radio fluxes seems to indicate that either:

- Black hole spin is not important for the formation of jets in the low/hard state of black holes. This may be natural if the jets are formed at large distances from the black hole.
- Black hole spin *is* important, and all the binary black holes have about the same (dimensionless) spin parameter. This may be natural since they all originate in rotating massive stars (c.f. radio pulsars).

In this context it may well be the case that even if black hole spin is not important for the low/hard state, it may well still be for the (transient) relativistic ejections which show a much greater scatter (although this may also be attributed to stronger beaming and less comprehensive coverage of light curves – Fender & Kuulkers 2001; Gallo, Fender & Pooley 2003). Furthermore, it should be noted that these conclusions

are rather contrary to those of Cui, Zhang & Chen (1998) who conclude that (a) most binary black holes are only slowly spinning, (b) only rapidly spinning black holes produce radio jets.

#### 9.10 Conclusions

In this review I have attempted to summarise our observational understanding of the phenomena of jets from X-ray binaries. In the process I have lightly, but no more, touched on various interpretations currently at large in the literature.

It is interesting to note that, whereas they were poorly investigated or understood one decade ago, these jets are now being considered as possible explanations for many exotic or high energy phenomena. Not only do they clearly emit from 100s of MHz to at least several keV, a range of  $10^{10}$  in photon energy, but they may be important sites of particle acceleration in the ISM and even sources of neutrinos. One thing seems clear - they are *powerful* and need to be carefully considered when attempting to describe the physics of accretion onto compact objects. This author has no doubt that the next decade will provide yet more excitement and surprises in this field.

#### Acknowledgements

The author would like to thank Catherine Brocksopp, Stephane Corbel, Elena Gallo, Sebastian Heinz, Thomas Maccarone, Sera Markoff and Simone Migliari for a careful reading of the manuscript and numerous useful suggestions.

```
Abramowicz M.A., Kluzniak W., Lasota J.-P., 2002, A&A, 396, L31
Angelini L., White N.E., 2003, ApJ, 586, L71
Atoyan A.M., Aharonian F.A., 1999, MNRASm 302, 253
Bailyn C.D., Orosz J.A., McClintock J.E., Remillard R.A., 1995, Nature, 378, 157
Balbus S.A., Hawley J.F., 1991, ApJ, 376, 214
Ball K., Kesteven M.J., Campbell-Wilson D., Turtle A.J., Hjellming R.M., 1995, MNRAS 273, 722
Baring M.G., Harding A.K., 1997, ApJ, 491, 663
Becker P.A., Subramanian P., Kazanas D., 2001, ApJ, 552, 209
Beckert T., 2000, ApJ, 539, 223
Belloni T., 1998, New Astronomy Reviews, 42, 585
Belloni T., Mèndez M., van der Klis M., Hasinger G., Lewin W.H.G., van Paradijs J., 1996, ApJ,
  472, L107
Belloni T., Mèndez M., van der Klis M., Lewin W.H.G., Dieters S., 1998, ApJ, 519, L159
Belloni T., Klein-Wolt M., Mèndez M., van der Klis M., van Paradijs J., 2000, A&A, 355, 271
Belloni T., Migliari S., Fender R.P., 2000, A&A, 358, L29
Bildsten L., et al., 1997, ApJ Supp. Ser., 113, 367
Blandford R., 2002, In: Relativistic flows in Astrophysics, Springer Lecture notes in Physics, vol.
  589, p. 227
Blandford R., Eichler, 1987, Physics Reports 154, 1
Blandford R.D., K"onigl A., 1979, ApJ, 232, 34
Blandford R.D., Payne D.G., 1982, MNRAS, 199, 883
Blandford R.D., Begelman M.C., 1999, MNRAS, 303, L1
Blandford R.D., Znajek R.L., 1977, MNRAS, 179, 433
Blandford R.D., McKee C.F., Rees M.J., 1977, Nature, 267, 211
Bodo G., Ghisellini G., 1995, ApJ, 441, L69
Bradshaw C.F., Geldzahler B.J., Fomalont E.B., 1997, ApJ, 481, 489
Bradshaw C.F., Fomalont E.B., Geldzahler B.J., 1999, ApJ, 512, L121
Brinkmann W., Aschenbach B., Kawai N., 1996, A&A, 312, 306
Brocksopp C., Fender R.P., Larionov V., Lyuty V.M., Tarasov A.E., Pooley G.G., Paciesas W.S.,
  Roche P., 1999, MNRAS, 309, 1063
Brocksopp C., Jonker P.G., Fender R.P., Groot P.J., van der Klis M., Tingay S.J., 2001, MNRAS,
 323, 517
Butt Y.M., Maccarone T.J., Prantzos N., 2003, ApJ, 587, 748
Campana S., Stella L., 2000, ApJ, 541, 849
Celotti A., Ghisellini G., 2003, MNRAS, submitted
Charles P.A., 1998, In: Theory of Black Hole Accretion Disks, Eds M. A. Abramowicz, G.
  Bjornsson, and J. E. Pringle. Cambridge University Press, 1998., p.1
```

Corbel S., Fender R.P., Tzioumis A.K., Nowak M., McIntyre V., Durouchoux P., Sood R., 2000,

A&A, 359, 251

Chen W., Shrader C.R., Livio M., 1997, ApJ, 491, 312
Colbert E.J.M., Mushotzky R.F., 2002, ApJ, 519, 89
Corbel S., Fender R.P., 2002, ApJ, 573, L35

Corbel S. et al., 2001, ApJ, 554, 43

Corbel S., Fender R.P., Tzioumis A.K., Tomsick J.A., Orosz J.A., Miller J.M., Wijnands R., Kaaret P., 2002, Science, 298, 196

Cowley A.P., Schmidtke P.C., Crampton D., Hutchings J.B., 1998, ApJ, 504, 854

Crocker M.M., Davis R.J., Spencer R.E., Eyres S.P.S., Bode M.F., Skopal A., 2002, MNRAS, 335, 1100

Cui W., Zhang S.N., Chen W., 1998, ApJ, 492, L53

Das T.K., 1999, MNRAS, 308, 201

Das T.K., Rao A.R., Vadawale S.V., 2003, MNRAS, 343, 443

Di Stefano C., Guetta D., Waxman E., Levinson A., 2002, ApJ, 575, 378

Dhawan V., Mirabel I.F., Rodríguez L.F., 2000, ApJ, 543, 373

Dubner G.M., Holdaway M., Goss W.M., Mirabel I.F., 1998, AJ, 116, 1842

Dubus G., Rutledge R.E., 2002, MNRAS, 336, 901

Eikenberry S.S., Matthews K., Morgan E.H., Remillard R.A., Nelson R.W., 1998a, ApJ, 494, L61

Eikenberry S.S., Matthews K., Murphy T.W. Jr, Nelson R.W., Morgan E.H., Remillard R.A., Muno M., 1998b, ApJ, 506, L31

Eikenberry S.S., Matthews K., Muno M., Blanco P.R., Morgan E.H., Remillard R.A., 2000, ApJ, 532, L33

Eikenberry S.S., Cameron P.B., Fierce B.W., Kull D.M., Dror D.H., Houck J.R., Margon B., 2001, ApJ, 561, 1027

Eikenberry S.S., Matthews K., Muno M., Blanco P.R., Morgan E.H., Remillard R.A., 2002, ApJ, 523, L33

Esin A.A., McClintock J.E., Narayan R., 1997, ApJ, 489, 865

Falcke H., Biermann P.L., 1996, A&A, 308, 321

Falcke H., Biermann P.L., 1999, A&A, 342, 49

Falcke H., Körding E., Markoff S., 2003, A&A, in press (astro-ph/0305335)

Fender R.P., 2001, MNRAS, 322, 31

Fender R.P., 2003, MNRAS, in press

Fender R.P., Hendry M.A., 2000, MNRAS, 317, 1

Fender R.P., Pooley G.G., 1998, MNRAS, 300, 573

Fender R.P., Pooley G.G., 2000, MNRAS, 318, L1

Fender R.P., Kuulkers E., 2001, MNRAS, 324, 923

Fender R.P., Gallo E., Jonker P.G., 2003, MNRAS, 343, L99

Fender R.P., Pooley G.G., Brocksopp C., Newell S.J., 1997, MNRAS, 290, L65

Fender R.P., Bell Burnell S.J., Williams P.M., Webster A.S., 1996, MNRAS, 283, 798

Fender, R., Spencer, R., Tzioumis, T., Wu, K., van der Klis, M., van Paradijs J., Johnston H., 1998, ApJ, 506, L21

Fender, R.P., Garrington, S.T., McKay, D.J., Muxlow, T.W.B., Pooley, G.G., Spencer, R.E., Stirling, A.M., Waltman, E.B., 1999a, MNRAS, 304, 865

Fender R. et al., 1999b, ApJ, 519, L165

Fender R., Rayner D., Norris R., Sault R.J., Pooley G., 2000a, ApJ, 530, L29

Fender R.P., Pooley G.G., Durouchoux P., Tilanus R.P.J., Brocksopp C., 2000b, MNRAS, 312, 853

Fender R.P., Hjellming R.M., Tilanus R.P.J., Pooley G.G., Deane J.R., Ogley R.N., Spencer R.E., 2001, MNRAS, 322, L23

Fender R.P., Rayner D., McCormick G., Muxlow T.W.B., Pooley G.G., Sault R.J., Spencer R.E., 2002, MNRAS, 336, 39

Feretti L., et al., 2001, Proceedings of the 5th EVN Symposium, Eds. J. Conway, A. Polatidis, R. Booth, Onsala Observatory, Sweden (June 2000), p. 171

Fomalont E.B., Geldzahler B.J., 1991, ApJ, 383, 289

Fomalont E.B., Geldzahler B.J., Bradshaw C.F., 2001a, ApJ, 553, L27

Fomalont E.B., Geldzahler B.J., Bradshaw C.F., 2001b, ApJ, 558, 283

Gaensler B.M., Stappers B.W., Getts T.J., 1999, ApJ, 522, L117

Gallant Y.A., 2002, In: Relativistic flows in Astrophysics, Springer Lecture notes in Physics, vol. 589, p. 24

Gallo E., Fender R.P., Pooley G.G., 2002, Proceedings '4th Microquasar Workshop: New Views on MICROQUASARS, Eds. P. Durouchoux, Y. Fuchs, and J. Rodríguez. Published by the Center for Space Physics: Kolkata (India), p. 201.

Gallo E., Fender R.P., Pooley G.G., 2003, MNRAS, 344, 60

Garcia M.R., Grindlay J.E., Molnar L.A., Stella L., White N.E., Seaquist E.R., 1988, ApJ, 328, 552

Garcia M.R., McClintock J.E., Narayan R., Callanan P., Barret D., Murray S.S., 2001, ApJ, 553, L47

Garcia M.R., Miller J.M., McClintock J.E., King A.R., Orosz J., 2003, ApJ, 591, 388

Geldzahler B.J. et al., 1983, ApJ, 273, L65

Georganopoulos M., Aharonian F.A., Kirk J.G., 2002, A&A, 388, L25

Gierlinksi M., Zdziarski A.A., Poutanen J., Coppi P.S., Ebisawa K., Johnson N.W., 1999, MNRAS, 309, 496

Gomez J.-L., Marscher A.P., Alberdi A., Jorstad S.G., Garcia-Miro C., 2000, Science, 289, 2317

Gregory P.C. et al., 1972, Nature Phys. Science, 239, 114

Gregory P.C., Neish C., 2002, ApJ, 580, 1133

Hannikainen D., Hunstead R.W., Campbell-Wilson D., 1998, A&A, 337, 460

Hannikainen D.C., Hunstead R.W., Campbell-Wilson D., Wu K., McKay D.J., Smits D.P., Sault R.J., 2000, ApJ, 540, 521

Hannikainen D., Campbell-Wilson D., Hunstead R., McIntyre V., Lovell J., Reynolds J., Tzioumis T., Wu, K., 2001, Ap&SSS, 276, 45

Harmon B.A. et al., 1995, Nature, 374, 703

Hasinger G., van der Klis M., 1989, A&A, 225, 79

Hawley J.F., Balbus S.A, 2002, ApJ, 573, 738

Heinz S., 2002, A&A, 388, L40

Heinz S., Sunyaev R., 2002, A&A, 390, 751

Heinz S., Sunyaev R., 2003, MNRAS, 343, L59

Hjellming R.M., Wade C.M., 1971a, ApJ, 164, L1

Hjellming R.M., Wade C.M., 1971b, ApJ, 168, L21

Hjellming R.M., Johnston K.J., 1981a, Nature, 290, 100

Hjellming R.M., Johnston K.J., 1981b, ApJ, 246, L141

Hjellming R.M., Johnston K.J., 1988, ApJ, 328, 600

Hjellming R.M., Gibson D.M., Owen F.N., 1975, Nature, 256, 111

Hjellming, R.M., Han, X., 1995, Radio properties of X-ray binaries. In: Lewin, W.H.G., van Paradijs, J., van der Heuvel, E.P.J. (Eds.), X-ray binaries, Camridge University Press, Cambridge, 308–330

Hjellming, R.M., Rupen, M.P., 1995, Nature, 375, 464

Hjellming R.M., Han X., Cordova F.A., Hasinger G., 1990a, A&A, 235, 147

Hjellming R.M. et al., 1990b, ApJ, 365, 681

Hjellming R.M., Han X., Roussel-Dupre D., 1990c, IAU Circ 5112

Hjellming R.M. et al., 2000a, ApJ, 544, 977

Hjellming R.M., Rupen M.P., Mioduszewski A.J., Narayan R., 2000b, ATel 54

Homan J., van der Klis M., Wijnands R., Vaughan B., Kuulkers E., 1998, ApJ, 499, L41

Homan J., Wijnands R., van der Klis M., Belloni T., van Paradijs J., Klein-Wolt M., Fender R., Mèndez M., 2001, ApJS, 132, 377

Hughes P.A., 1991, (Ed), 'Beams and Jets in Astrophysics', Cambridge Astrophysics Series vol. 19, CUP, UK

Hynes R.I., Mauche C.W., Haswell C.A., Shrader C.A., Cui W., Chaty S., 2000, ApJ, 539, L37

Hynes R.I. et al., 2003, MNRAS, in press (astro-ph/0306626)

Jain R.K., Bailyn C.D., Orosz J.A., McClintock J.E., Remillard R.A., 2001, ApJ, 554, L181

Janiuk A., Czerny B., Zycki P.T., 2000, MNRAS, 318, 180

Junor W., Biretta J.A, Libio M., 1999, Nature, 401, 891

Kaaret P., Corbel S., Tomsick J.A., Fender R., Miller J.M., Orosz J.A., Tzioumis T., Wijnands R., 2003, ApJ, 582, 945

Kaaret P., Corbel S., Prestwich A.H., Zezas A., 2003, Science, 299, 365

Kaiser C.R., Hannikainen D.C., 2002, MNRAS, 330, 225

Kaiser C.R., Sunyaev R., Spruit H.C., 2000, A&A, 356, 975

Kanbach G., Straubmeier C., Spruit H.C., Belloni T., 2001, Nature, 414, 180

Kaufman Bernado M.M., Romero G.E., Mirabel I.F., 2002, A&A, 385, L10

King A.R., Davies M.B., Ward M.J., Fabbiano G., Elvis M., 2001, ApJ, 522, L109

Klein-Wolt M., Fender R.P., Pooley G.G., Bellpni T.M., Morgan E.H., Migliari S., van der Klis M., 2002, MNRAS, 331, 745

Koide S., Shibata K., Kudoh T., Meier D.L., 2002, Science, 295, 1688

Körding E., Falcke H., Markoff S., 2002, A&A, 382, L13

Kudoh T., Matsumoto R., Shibata K., 2002, PASJ, 54, 121

Kuulkers E., Fender R.P., Spencer R.E., Davis R.J., Morison I., 1999, MNRAS, 36, 919

Lada C.J., 1985, ARA&A, 23, 267

Levinson A., Blandford R., 1996, ApJ, 456, L29

Lithwick Y., Sari R., 2001, ApJ, 555, 540

Liu Q.Z., van Paradijs J., van den Heuvel E.P.J., 2000, A&AS, 147, 25

Liu Q.Z., van Paradijs J., van den Heuvel E.P.J., 2001, A&A, 368, 1021

Livio M., 1999, Physics Reports, 311, 225

Livio M., Ogilvie G.I., Pringle J.E., 1999, ApJ, 512, 100

Livio M., Pringle J.E., King A.R., 2003, ApJ, 593, 184

Longair M.S., 1994, High energy Astrophysics, Volume 2 Stars, The galaxy and the interstellar medium, Cambridge University Press, Cambridge

Lynden-Bell D., 2003, MNRAS, 341, 1360

McClintock J.E., Garcia M.R., Caldwell N., Falco E.E., Garnavich P.M., Zhao P., 2001, ApJ, in press

McCollough M. et al., 1999, ApJ, 517, 951

Maccarone T.J., 2002, MNRAS, 336, 1371

Maccarone T.J., 2003, A&A, in press, (astro-ph/0308036)

Maccarone T.J., Gallo E., Fender R.P., MNRAS, submitted

Margon B., 1984, ARA&A, 22, 507

Markoff S., Falcke H., Fender R.P., 2001, A&A, 372, L25

Markoff S., Nowak M., Corbel S., Fender R., Falcke H., 2003, A&A, 397, 645

Marscher A.P., Jorstad S.G., Gomez J-L., Aller M.F., Terasranta H., Lister M.L., Stirling A.M., 2002, Nature, 417, 625

Marshall H.L., Canizares C.R., Schulz N.S., 2002, ApJ, 564, 941

Martí J., Mirabel I.F., Rodríguez L.F., Chaty S., 1998, A&A, 332, L45

Martí J., Mirabel I.F., Rodríguez L.F., Smith I.A., 2002, A&A, 386, 571

Martí J., Paredes J.M., Peracaula M., 2001, A&A, 375, 476

Martí n E.L., Casares J., Molaro P., Rebolo R., Charles P., 1994, ApJ, 435, 791

Mason K.O., Cordova F.A., White N.E., 1986, ApJ, 309, 700

Meier D.L., 1999, ApJ, 522, 753

Meier D.L., 2001, ApJ, 548, L9

Meier D.L., Edgington S., Godon P., Payne D.G., Lind K.R., 1997, Nature, 388, 350

Meier D.L., Koide S., Uchida Y., 2001, Science, 291, 84

Mèndez M., Belloni T., van der Klis M., 1998, ApJ, 499, L187

Meier D.L., 2001, ApJ, 548, L9

Merloni A., Fabian A.C., 2002, MNRAS, 322, 165

Merloni A., Di Matteo T., Fabian A., 2000, MNRAS, 318, L15

Merloni A., Heinz S., di Matteo T., 2003, MNRAS, in press (astro-ph/0305261)

Migliari S., Fender R.P., Mèndez M., 2002, Science, 297, 1673

Migliari S., Fender R.P., Rupen M., Jonker P., Klein-Wolt M., Hjellming R.M., van der Klis M., 2003, MNRAS, 342, L67

Miller J.M. et al., 2002a, ApJ, 578, 348

Miller J.M., Ballantyne D.R., Fabian A.C., Lewin W.H.G., 2002b, MNRAS, 335, 865

Mioduszewski A.J., Rupen M.P., Hjellming R.M., Pooley G.G., Waltman E.B., 2001, ApJ, 553, 766

Mirabel I.F., 1994, ApJS, 92, 369

Mirabel I.F., Rodríguez L.F., Cordier B., Paul J., Lebrun F., 1992, Nature, 358, 215

Mirabel, I.F., Rodríguez, L.F, 1994, Nature, 371, 46

Mirabel, I.F., Rodríguez, L.F, 1999, ARA&A, 37, 409

Mirabel I.F., Rodríguez L.F., Cordier B., Paul J., Lebrun F., 1992, Nature, 358, 215

Mirabel I.F., Bandyopadhyay R., Charles P.A., Shahbaz T., Rodríguez L.F., 1997, ApJ, 477, L45

Mirabel I.F., Dhawan V., Chaty S., Rodríguez L.F., Martí J., Robinson C.R., Swank J., Geballe T., 1998, A&A, 330, L9

Moore C.B., Rutledge R.E., For D.W., Guerriero R.A., Lewin W.H.G., Fender R.P., van Paradijs J., 2000, ApJ, 432, 1181

Motch C., Ilovaisky S.A., Chevalier C., Angerbault P., 1985, Space Science Reviews, 40, 219

Naik S., Rao A.R., 2000, A&A, 362, 691

Narayan R., Yi I., 1995, ApJ, 444, 231

Nobili L., 2003, ApJ, 582, 954

O'Dell, 1981, ApJ, 243, L147

Ogilivie G.I., Dubus G., 2001, MNRAS, 320, 4850

Ogilvie G.I., Livio M., 2001, ApJ, 553, 1580

Orosz J.A. et al. 2001, ApJ, 555, 480

Owen F.N., Balonek T.J., Dickey J., Terzian Y., Gottesman S.T., 1976, ApJ, 203, L150

Paragi Z., Fejes I., Vermeulen R.C., Schilizzi R.T., Spencer R.E., Stirling A.M., 2001, in: Schilizzi R.T., Vogel S., Paresce F., Elvis M. (eds.) Proc. IAU Symposium 205 "Galaxies and their constituents at the highest angular resolutions", ASP, p. 112

Paredes J.M., Martí J., Ribó M., Massi M., 2000, Science, 288, 2340

Paredes J.M., Ribó M., Ros E., Martí J., Massi M., 2002, A&A, 393, L99

Penninx W., 1989, in Proc: The 23rd ESLAB Symposium on Two Topics in X Ray Astronomy. Volume 1: X Ray Binaries, p. 185

Penninx W., Lewin W.H.G., Zijlstra A.A., Mitsuda K., van Paradijs J., 1988, Nature, 336, 146

Phinney E.S., 1982, MNRAS, 198, 1109

Pooley G.G., Fender R.P., 1997, MNRAS, 292, 925

Pooley G.G., Fender R.P., Brocksopp C., 1999, MNRAS, 302, L1

Portegies Zwart S.F., Lee C.H., Lee H.K., 1999, A&AS, 138, 503

Pottschmidt K., Wilms J., Nowak M.A., Heindl W.A., Smith D.M., Staubert R., 2000, A&A, 357, 2000

Poutanen J., 1998, In: Abramowicz, M. A., Björnsson, G., Pringle, J. E. (Eds), Theory of Black Hole Accretion Discs, Cambridge Contemporary Astrophysics, CUP, 1998, p.100

Priedhorsky W., Hasinger G., Lewin W.H.G., Middleditch J., Parmar A., Stella L., White N., 1986, ApJ, 306, L91

Pugliese G., Falcke H., Biermann P.L., 1999, A&A, 344, L37

Rees M.J., 1966, Nature, 211, 468

Rees M.J., Begelman M.C., Blandford R.D., Phinney E.S., Nature, 1982, 295, 17

Reig P., Mèndez M., van der Klis M., Ford E.C., 2000, ApJ, 530, 916

Reipurth B., Bally J., 2001, ARA&A, 39, 403

Ribó M., Paredes J.M., Romero G.E., Benaglia P., Martí J., Fors O., Garcia-Sanchez J., 2002, A&A, 384, 954

Rodríguez L.F., Mirabel I.F., 1999, ApJ, 511, 398

Rodríguez L.F., Mirabel I.F., Martí J., 1992, ApJ, 401, L15

Romero G.E., Kaufman Bernado M.M., Mirabel I.F., 2002, A&A, 393, L61

Rupen M., Hjellming R.M., Mioduszewski A.J., 1998, IAU Circ. 6938

Rupen M., Hjellming R.M., Mioduszewski A.J., 2002, New Views on MICROQUASARS, the Fourth Microquasars Workshop, Institut d'Etudes Scientifiques de Cargese, Corsica, France,

May 27 - June 1, 2002. Edited by Ph. Durouchoux, Y. Fuchs, and J. Rodriguez. Published by the Center for Space Physics: Kolkata (India), p. 213.

Sams B., Eckart A., Sunyaev R., 1996, Nature, 382, 47

Sari R., Piran T., Halpern J.P., 1999, ApJ, 519, L17

Schnerr R.S., Reerink T., van der Klis M., Homan J., Mendex M., Fender R.P., Kuulkers E., 2003, A&A, 406, 221

Shapiro P.R., Milgrom M., Rees M.J., 1986, ApJS, 60, 393

Shirey R.E., Bradt H.V., Levine A.M., 1999, ApJ, 517, 472

Sokoloski J.L, Kenyon S.J., 2003, ApJ, 584, 1021

Spencer R.E., 1979, Nature, 282, 483

Spruit H.C., Kanbach G., 2002, A&A, 391, 225

Stewart, R.T., Caswell J.L., Haynes, R.F., Nelson, G.J., 1993, MNRAS, 261, 593

Stirling A., Spencer R., Garrett M., 1998, New Astronomy Reviews, 42, 657

Stirling A.M., Spencer R.E., de la Force C.J., Garrett M.A., Fender R.P., Ogley R.N., 2001, MNRAS, 327, 1273

Strickman M.S., Tavani M., Coe M.J., Steele I.A., Fabregat J., Martí J., Paredes J.M., Ray P.S., 1998, ApJ, 497, 419

Tagger M., Pellat R., 1999, A&A, 349, 1003

Tan J., Lewin W.H.G., Hjellming R.M., Penninx W., van Paradijs J., van der Klis M., 1991, ApJ, 385, 314

Tananbaum H., Gursky H., Kellogg E., Giacconi R., Jones C., 1972, ApJ, 177, L5

Tingay, S.J. et al., 1995, Nature, 374, 141

Tomsick J.A., Corbel S., Fender R.P., Miller J.M., Orosz J.A., Tzioumis T., Wijnands R., Kaaret P., 2003, ApJ, 592, 933

Turner N.J., Stones J.M., Sano T., 2002, ApJ, 566, 148

van der Klis, M., 1995, In: Lewin, W. H. G., van Paradijs, J., van der Heuvel, E. P. J. (Eds.), X-ray binaries, Camridge University Press, Cambridge, 252

van der Laan, H. 1966, Nature, 211, 1131

van Paradijs, J., 1995, In: Lewin, W. H. G., van Paradijs, J., van der Heuvel, E. P. J. (Eds.), X-ray binaries, Camridge University Press, Cambridge, 536

Vadawale S.V., Rao A.R., Chakrabarti S.K., 2001, A&A, 372, 793

Varniere P., Tagger M., 2002, A&A, 394, 329

Waltman E.B., Foster R.S., Pooley G.G., Fender R.P., Ghigo F.D., 1996, AJ, 112, 2690

Wardle J.F.C., Homan D.C., 2001, In Proc 'Particles and Fields in Radio Galaxies', Eds. Robert A. Laing and Katherine M. Blundell, ASP Conference Series Volume 250, San Francisco: Astronomical Society of the Pacific, 2001, p.152

Wardle J.F.C., Homan D.C., Ojha R., Roberts D.H., 1998, Nature, 395, 457

Zdziarski A.A., Lubinski P., Gilfanov M., Revnivtsev M., 2003, MNRAS,342, 355

Zensus J.A., Pearson T.J. (Eds), 1987, Superluminal Radio Sources, Cambridge University Press Zhang S.N., Mirabel I.F., Harmon B.A., Kroeger R.A., Rodríguez L.F., Hjellming R.M., Rupen M.P., 1997, In Proc. Fourth Compton Symposium, C.D. Dermer, M.S. Strickman & J.D. Kurfess (Eds), AIP Conf. Proc. 410, p. 141