# 9

# Jets from X-ray binaries

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## 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 recognized 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), "non-thermal" spectra and polarization 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). 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 the velocity parameter $\beta = v/c$) 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).

*Compact Stellar X-Ray Sources,* eds. Walter Lewin and Michiel van der Klis.

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 behavior 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 behavior becomes, and this is a rapidly advancing field. In this chapter I shall attempt, subjectively, to describe the state of the research 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. Figure 9.1 presents *radio* images of relativistic ejections from three outbursting X-ray binaries on sub-arcsecond angular scales. Figure 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 our 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 "non-thermal" spectra, high brightness temperatures and, in some cases, high degree of linear polarization. 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 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, for example, X-ray state changes and X-ray transients reveal an optically thin spectrum above some frequency, from which the underlying electron population can be derived. If the underlying electron distribution is a power law of the form $N(E)\,\mathrm{d}E \propto E^{-p}\,\mathrm{d}E$ then observations of the spectral index ($\alpha = \Delta \log S_\nu / \Delta \log \nu$, i.e., $S_\nu \propto \nu^\alpha$; note the lack of a minus sign in this definition contrary to common practice in X-ray spectroscopy) 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, $-0.4 \geq \alpha \geq -0.8$, indicate $1.8 \leq p \leq 2.6$. 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 $V$ of synchrotron emitting plasma can be obtained from a simple estimate of the monochromatic

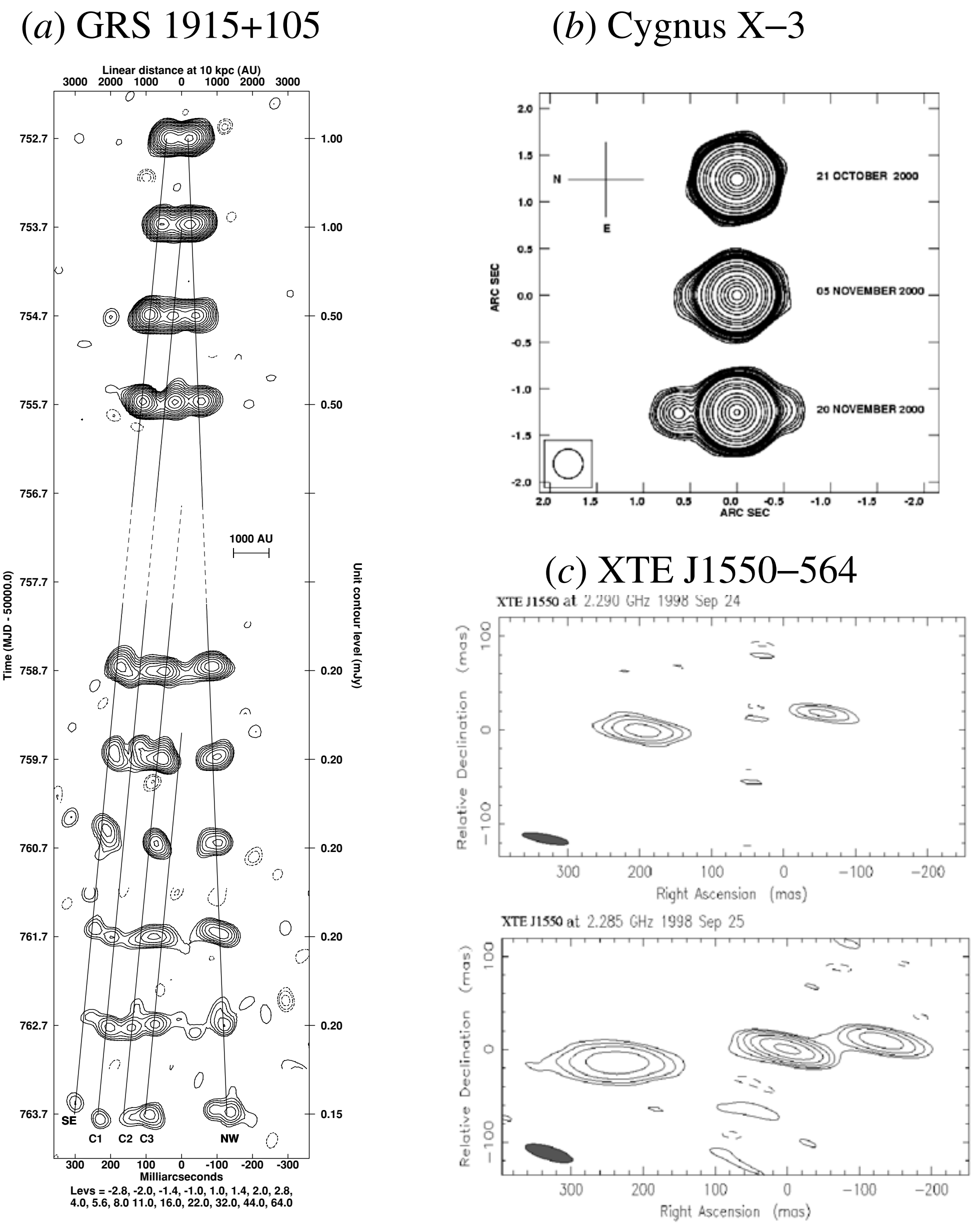


Fig. 9.1. Radio images of relativistic jets from X-ray binaries. Panel (*a*) shows a sequence of images of "superluminal" relativistic ejections from GRS 1915+105 observed with MERLIN (Fender *et al.* 1999a). Panel (*b*) is a sequence of slower, arcsec-scale jets from Cyg X-3 (Martí *et al.* 2002), which may be the jet–ISM interaction zones of the inner, more relativistic jet (Mioduszewski *et al.* 2000). Panel (*c*) presents two VLBI images from Hannikainen *et al.* (2001) 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.

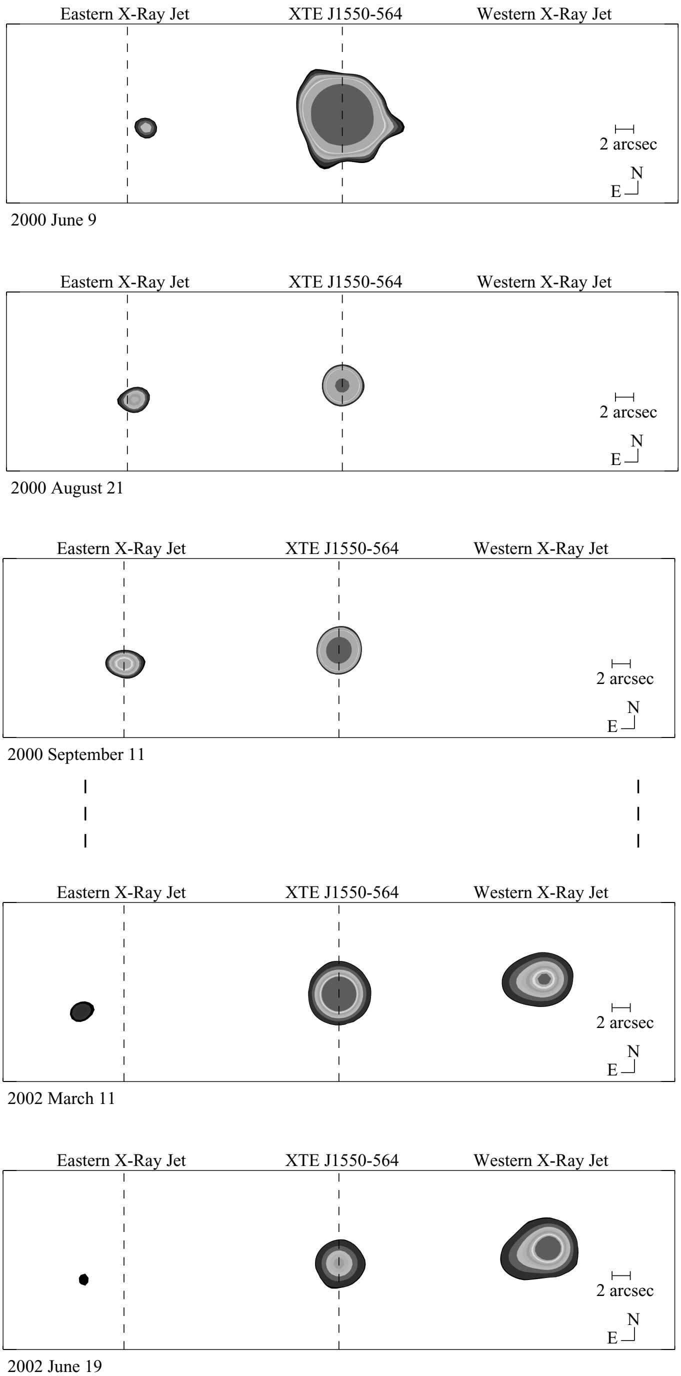


Fig. 9.2. Chandra images of moving X-ray jets from the black hole transient XTE J1550–564 (Corbel *et al*. 2003; see also Kaaret *et al*. 2003 and Tomsick *et al*. 2003). The core is the central component, the "approaching" jet to the left (East) and the "receding" jet to the right (West). These remarkable 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.

luminosity $L_\nu$ at a given frequency $\nu$ associated with that volume:

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

where $\eta = (1 + \epsilon_{\rm p}/\epsilon_{\rm e})$, and $\epsilon_{\rm p}/\epsilon_{\rm e}$ represents the ratio of energy in protons to that in electrons, and assuming $p = 2$. It is generally assumed that $\epsilon_{\rm p}/\epsilon_{\rm e} \sim 0$ 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

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

The related mean power into the ejection event

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

The 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

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

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

$$\gamma_{\rm e} \sim 30 \left(\frac{\nu}{\rm GHz}\right)^{1/2} \left(\frac{B}{\rm G}\right)^{-1/2} \tag{9.5}$$

Figure 9.3 shows a 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$^{-1}$, many orders of magnitude greater than the observed radiative radio luminosity. The corresponding equipartition field can be estimated as $\sim$0.5 G, 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.

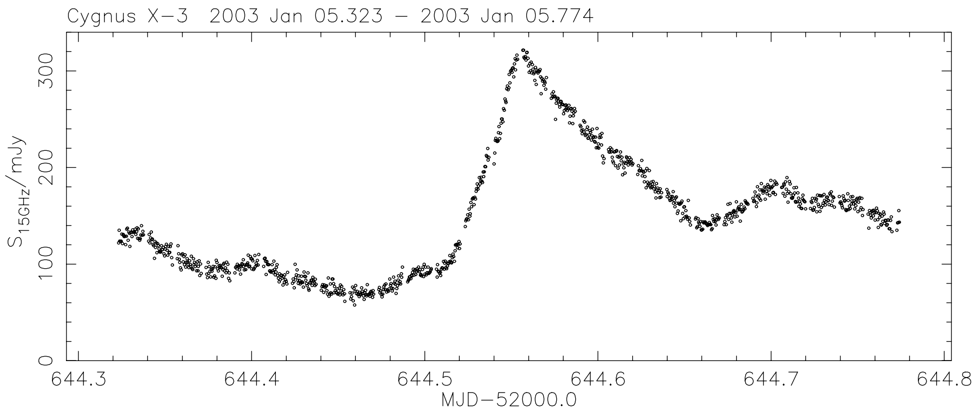


Fig. 9.3. Observation of a radio flare event from the jet source Cyg X-3 at 15 GHz. The rise time of the event $\sim$0.04 d, allows an estimation of the size of the region associated with the event, and thus the minimum energy. Observations from the Ryle Telescope (Guy Pooley, private communication).

### *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 characterized by optically thin spectra and are associated with, for example, 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 that 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 disk. 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.* 2002).

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 and Rodríguez (1994) first reported apparent superluminal motions from a galactic source, GRS 1915+105. The apparent velocity parameter of the observed motion of the features on the sky, $\beta_{\mathrm{obs}}$, is related to the observed proper motion by

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

This apparent velocity parameter is related to that of the intrinsic velocity $\beta_{\mathrm{int}}$ by

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

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., $\beta_{\mathrm{obs}} > 1$) requires $\beta_{\mathrm{int}} \geq 0.7$, indicating that at least mildly relativistic intrinsic velocities are required to achieve the effect (or a badly overestimated distance!). The associated relativistic Doppler shift $1 + \Delta\nu/\nu$ is given by

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

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 $\beta_{\mathrm{int}}$? As described in Mirabel & Rodríguez (1994), measurement of $\mu_{\mathrm{app}}$ and $\mu_{\mathrm{rec}}$ allows a determination of the following product:

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

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

Once the proper motions are measured, the angle of ejection, $\theta$, and consequently the intrinsic velocity, $\beta_{\mathrm{int}}$, are uniquely determined for every distance since

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

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

The variation of $\beta_{\mathrm{int}}$ 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 $\beta_{\mathrm{int}} = 1$ (i.e., $\Gamma = \infty$):

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

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

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

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 (Eq. 9.9). An object moving at angle $\theta$ to the line of sight with velocity $\beta_{\mathrm{int}}$(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 for example 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

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

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, Chapters 2 and 4), and possibly also in the "plateau" state of GRS 1915+105 (see Fender *et al.* 1999a), and the hard states of some neutron star atoll sources (see Section 2.5). Nevertheless, there are some clues that the jets may be mildly, but not highly, relativistic. Stirling *et al.* (2001), in direct imaging of the milliarcsec-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 *et al.* (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).

The observations of the luminous neutron star source 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 *et al.* 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 and Rodríguez (1994) it was widely accepted that X-ray binary jets could be characterized by Lorentz factors $\sim 2$ (i.e., while significantly relativistic, considerably less so than the most extreme examples of AGN jets). However, in Fender *et al.* (1999) it was 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 in practice easily be

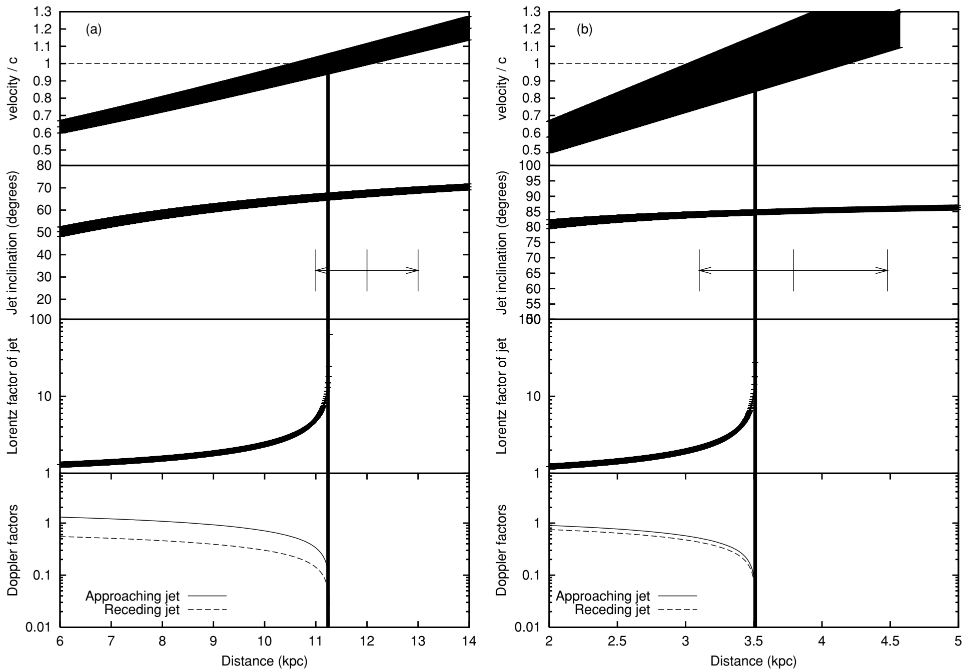


Fig. 9.4. Variation of solutions to velocity, angle to line of sight, Lorentz factor and Doppler factors for (*a*) GRS 1915+105 and (*b*) GRO J6155–40, as a function of distance, based upon observations of proper motions. When compared with the (relatively accurate) distance estimates it is clear that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

used to place an upper limit on the Lorentz factor $\Gamma$ of a highly relativistic flow, due to the steep dependence of this quantity on $d$ near $d_{\rm max}$ when $\Gamma$ is large. 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), no upper bound can be set on the Lorentz factor of the jets by observations of proper motions. Nevertheless, Fender and Kuulkers (2001) concluded that the mean bulk Lorentz factor for transients was likely to be $\leq 5$ since higher values would probably destroy the observed correlation between radio and X-ray peak fluxes (unless X-rays 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); second, the observations of Sco X-1 (Fomalont *et al.* 2001a,b) show us that the Lorentz factor (and hence boosting) of the energizing 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 confirmed 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.

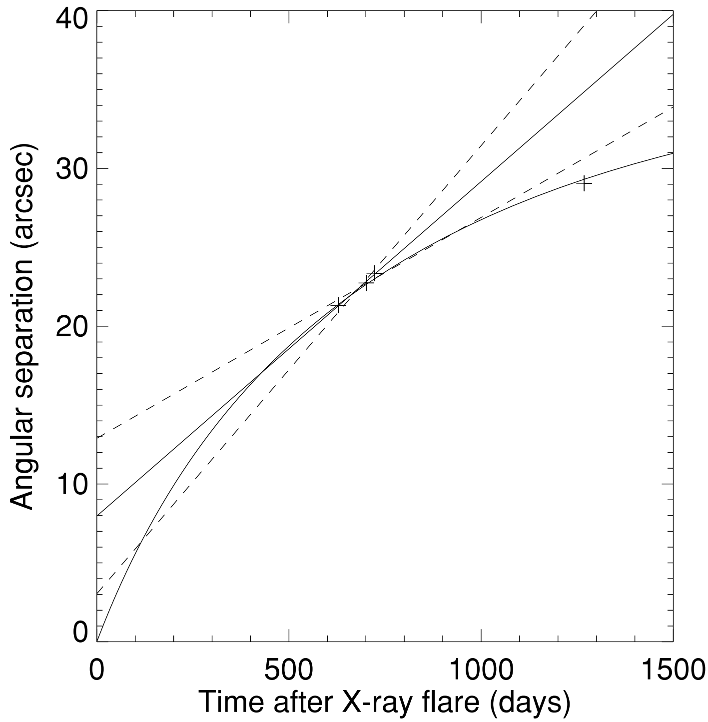


Fig. 9.5. Deceleration of X-ray jets from XTE J1550–564. Comparing a lower limit on the early proper motions on VLBI scales (Hannikainen *et al.* 2001) with subsequent measurements of the X-ray jets (Fig. 9.2) with Chandra, indicates a steady slow-down of the jets. A large fraction of the dissipated 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).

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 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 interstellar medium (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 is nothing to indicate that either the original flare event or the surrounding ISM are particularly unusual in any way).

To summarize, 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 ~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 disk (see e.g., Ogilivie & Dubus 2001 for a discussion). Hjellming and Rupen (1995) suggested a precession period for GRO J1655–40 that was very close to the subsequently determined orbital period (Section 5.3.3); similarly there seems to be marginal evidence for precession in the jets of GRS 1915+105 (Fender *et al.* 1999a; see also Rodríguez & Mirabel 1999). Kaufman Bernado *et al.* (2002) and Romero *et al.* (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 *et al.* 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 ($\geq$arcsec) X-ray jets have been observed from both SS 433 and XTE J1550–564 (Migliari *et al.* 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 ionized iron and are consistent with thermal emission from a plasma at $\sim 10^7$ 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 that 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 do not 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 and Pooley (2000) did this for the radio–mm–infrared oscillations from GRS 1915+105 (Fig. 9.10) 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 and 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.

Yet another approach to looking for emission lines or balancing energetics is polarization – in particular circular polarization holds the promise of a unique insight into the conditions in the emitting plasma (e.g., Wardle *et al.* 1998; Wardle & Homan 2001). Circular polarization has been detected in the radio emission of three X-ray binaries – SS 433 (Fender *et al.* 2000a), 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 polarization 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 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:

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

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:

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

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 $R \geq 8\ {\rm R_\odot}$. Typical binary separations for low-mass X-ray binaries are smaller than this (Section 5.3); 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 $\geq 15\ {\rm R_\odot}$. 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 *et al.* 2002 for the rather different case of CI Cam). Note that it is well known that beamed (i.e., relativistically aberrated) emission can display apparent brightness temperatures $\gg 10^{12}$ 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 that are either in the "low/hard" X-ray state (Section 9.4), or are undergoing a major transient outburst (Chapters 2, 4 and 5), 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 (Section 2.5.2.1). The lower luminosity, low magnetic field systems, which may be crudely lumped together as "atoll" sources (see also Section 2.4.2), *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 30 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 that are in persistent "soft" states).

## 9.4 Disk–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 disk–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 (below). Furthermore, McCollough *et al.* (1999) had reported the bimodal behavior of the radio–X-ray correlations in Cyg X-3, undoubtedly related to the changing disk–jet coupling outlined below.

Black holes exhibit, broadly speaking, several different kinds of X-ray "state" (Chapters 2 and 4). The two most diametrically opposed, which serve to illustrate the relation of jet formation to accretion, can be briefly summarized as:

- **Low/hard (and "off") state:** in this state the X-ray spectrum is dominated by a broad-band component which can be fit with a power law of photon index $\sim$1.6, often with a cutoff around 100 keV. Minor additional components to the X-ray spectrum include (sometimes) a weak "blackbody" (accretion disk) component, a "reflection" component and a relatively weak gamma-ray tail. The X-ray power spectra indicate up to 40% r.m.s. variability is present with a "break" at frequencies of around a few Hz.
- **"High/soft" state:** in this state the X-ray spectrum is dominated by a "blackbody" component with a temperature around a few keV, with additional line features and a relatively strong gamma-ray tail. The X-ray power spectrum is much weaker, and can be characterized by a power law with an r.m.s. variability of only a few %.

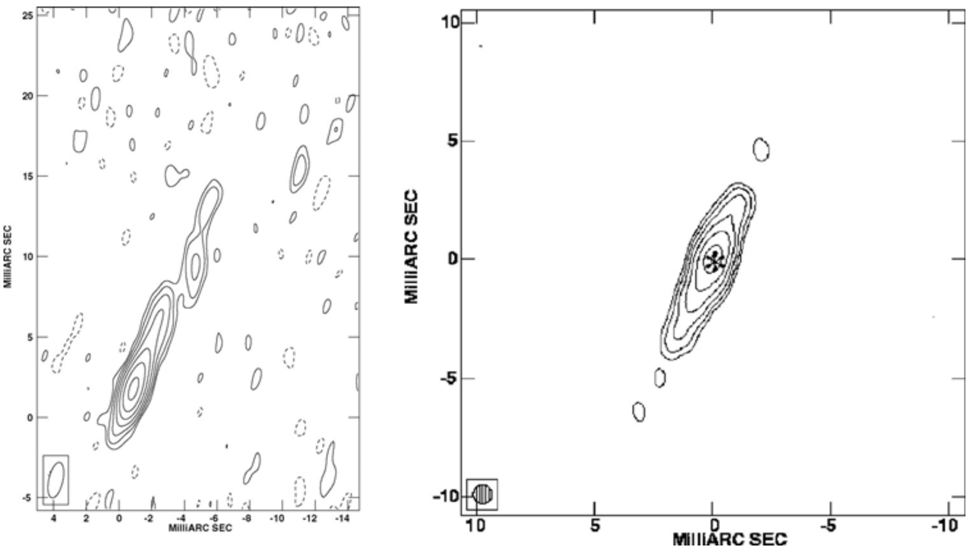


Fig. 9.6. AU-scale jets in persistent hard X-ray states, imaged with the VLBA. The left panel reveals a one-sided jet from Cygnus X-1 in the classical "low/hard" X-ray state (Stirling *et al.* 2001). The right panel shows the quasi-steady jet from GRS 1915+105 in hard "plateau" states (Dhawan *et al.*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

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

There are also "intermediate" and "very high" states, which actually both appear to be quasi-steady states that share some of the characteristics of both of the above states, but – crucially for their relation to jet formation – 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 X-ray 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 summarized thus: a "flat" spectrum (spectral index $\alpha \sim 0$) extending throughout the radio band and beyond to higher $\nu$, linear polarization at a level of $\sim$1–3% 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 has been 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 (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 milliarsecond-scale jet (Dhawan *et al.* 2000; Fig. 9.6 (right)), and the two galactic center low/hard state sources 1E 1740.7–2942 and GRS 1758–258 are both associated with large-scale radio lobes, indicating

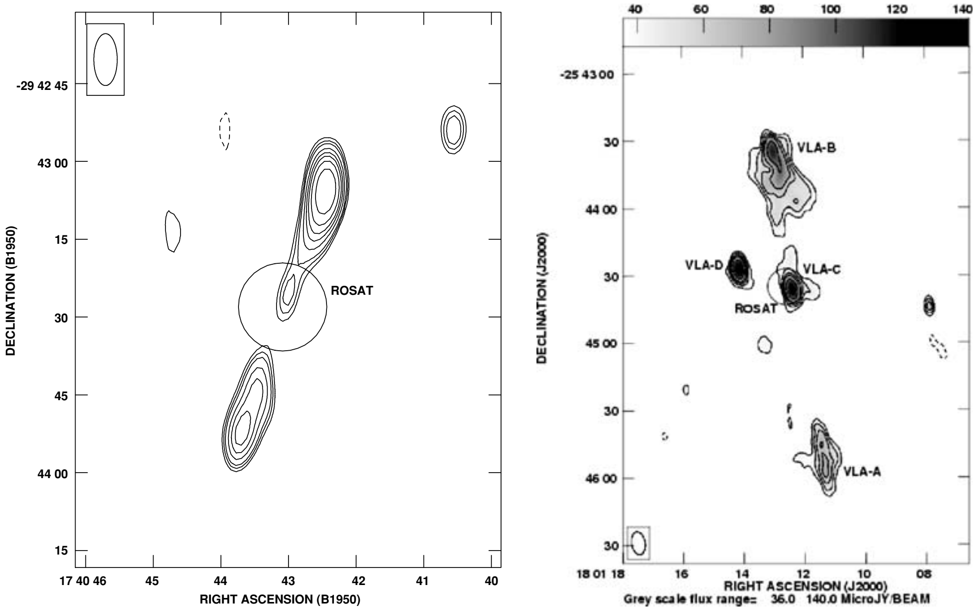


Fig. 9.7. Arcminute-scale radio jets from the galactic center low/hard state sources 1E 1740.7–2942 and GRS 1758–258. Both of these systems spend nearly all their time in the low/hard X-ray state, therefore an interpretation of these lobes is that they result from the long-term action of steady jets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

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 millimeter 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) behavior 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 lightcurve 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 *et al.* 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+105 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). 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 non-thermal components. Qualitatively similar infrared flares have been observed from Cyg X-3 (e.g., Mason *et al.* 1986; Fender *et al.* 1996) which with the benefit of hindsight seem likely to be synchrotron in origin. Finally, Sams *et al.* (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 $-1 \leq \alpha \leq 0$. A compilation of observations of the low/hard state source GX 339–4 appears to have identified just such a cutoff 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 that it produces, and (b) introducing a radiative efficiency, $\eta$, which is the ratio of radiated to total power (in the jet's rest frame). From this we can estimate the jet power as

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

where $L_{\mathrm{J}}$ is the radiative luminosity of the jet (i.e., the integral of $L_\nu$ over frequency), 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 radio band is synchrotron in origin, we can try to see how far this spectrum extends to other wavelengths. First, 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 cutoff to the synchrotron emission at low radio frequencies. In any case, while a low-frequency cutoff 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 μm (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 *et al.* (2001;

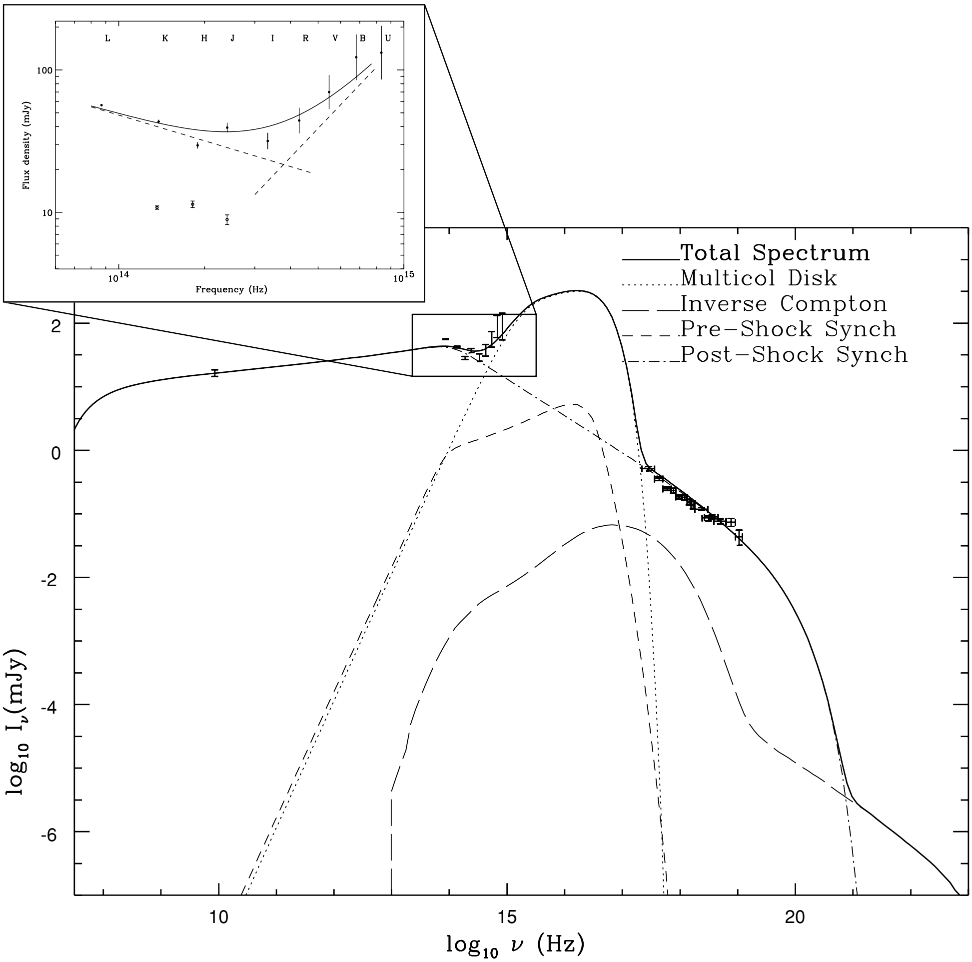


Fig. 9.8. Broadband jet-model fit to the radio–X-ray spectrum of GX 339–4 in the low/hard X-ray state (Markoff *et al.* 2003). The flat spectrum, self-absorbed, synchrotron component extends beyond the radio band and breaks to optically thin emission in the near-infrared (see insert, from Corbel & Fender 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 Comptonization models. The broadband spectrum and model fit are comparable to those for XTE J1118+480 while in the same X-ray state (Markoff *et al.* 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 an absence of 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 are 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 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, have found that the radio emission in the low/hard state scales as $L_{\text{radio}} \propto L^{b}_{\text{X-ray}}$ where $b \sim 0.7$ for X-rays up to at least 20 keV (possibly steepening towards a 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 *et al.* (2002, 2003) have found almost exactly the same correlation (in both normalization 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 $10^{-5}L_{\text{Edd}} \leq L_{\text{X}} \leq 10^{-2}L_{\text{Edd}}$ all systems are consistent with the same correlation with a very small scatter (less than one order of magnitude in radio flux), and that above a small percentage of $L_{\text{Edd}}$ the radio emission rapidly weakens (Gallo *et al.* 2003). Monte-Carlo simulations of Doppler-boosting effects indicate that such a small spread over such a large range in $L_{\text{X}}$ probably restricts the velocity of the jet in the low/hard state to $\beta = v/c \leq 0.8$ (Gallo *et al.* 2003; Fig. 9.9), unless the X-rays are also strongly beamed (in which case strong selection effects are at work).

*9.4.1.3 Jets in "quiescence"?*

Outside of periods of transient outburst, black hole candidates (BHCs) are typically observed with X-ray luminosities in the range $10^{-6}$–$10^{-9}$ Eddington, and are considered to be "quiescent" (see Chapter 4 and, 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 correlation discussed above down to such X-ray luminosities. Combining the estimates of jet power in the low/hard state with the $L_{\text{radio}} \propto L^{0.7}_{\text{X-ray}}$ 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 *et al.* 2003). Combining this result with the greater "radio loudness" (Section 9.5.3) of BHCs compared to neutron star (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 *et al.* 2003; see also Campana & Stella 2000; Garcia *et al.* 2001; Abramowicz *et al.* 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

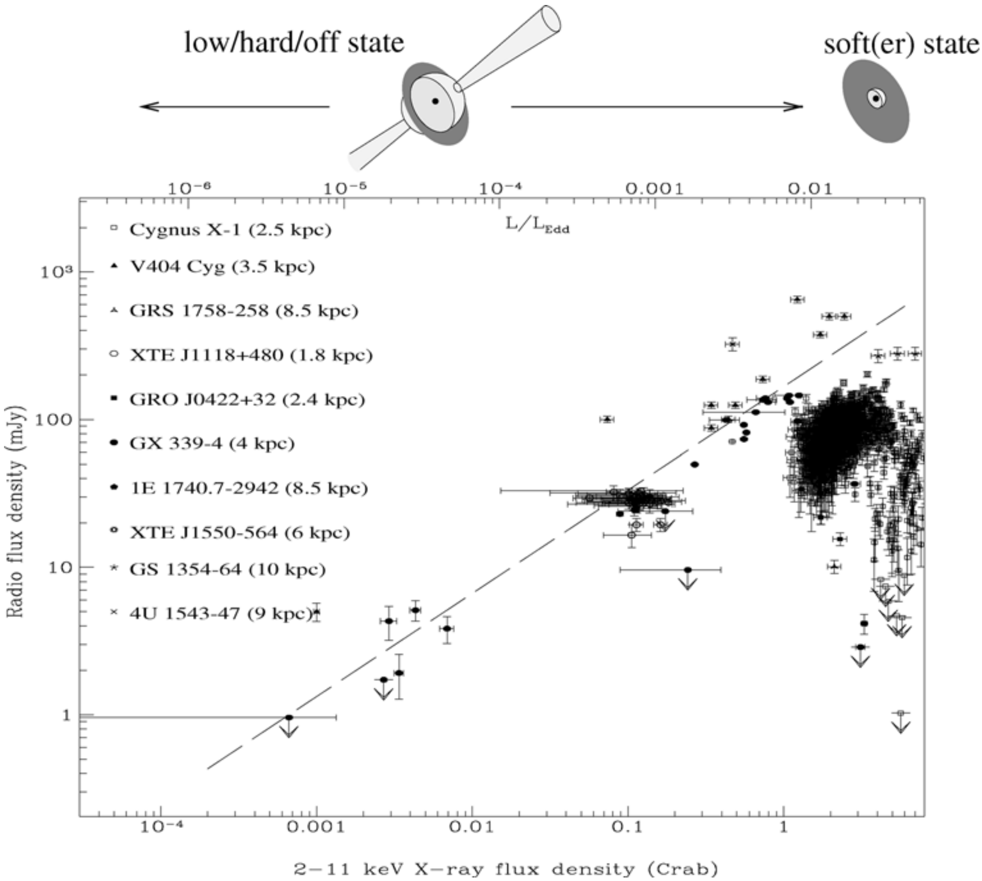


Fig. 9.9. (Quasi-)simultaneous radio and X-ray observations of black hole X-ray binaries, scaled to 1 kpc and corrected for absorption. Below a scaled X-ray flux of a few Crab (corresponding to ~1% of the Eddington luminosity for a 10 $M_\odot$ black hole), all black hole binaries follow a correlation of the form $S_{\rm radio} \propto S^{0.7}_{\text{X-ray}}$, 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 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 *et al.* (2003); see also Corbel *et al.* (2001, 2002).

Hjellming *et al.* 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 realized 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" disk-dominated states the radio jet was more than an order of magnitude weaker than in the low/hard state, and perhaps non-existent.

Comprehensive radio and X-ray monitoring of Cyg X-1 has revealed that the suppression of the radio emission occurs rather rapidly once at a bolometric luminosity of a small percentage Eddington the transition to the high/soft state occurs (Gallo *et al.* 2003; Maccarone 2003). Given that there are no observed counter-examples, we conclude that the soft X-ray state 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 Chpaters 2 and 4 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 an interesting fact that this state can occur over quite a large range in bolometric X-ray luminosity (as can the low/hard and high/soft states, see Homan *et al.* 2001; Sections 2.5.1 and 4.3).

Belloni (1998) suggested that the behavior 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 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 (Section 2.10.3 and, 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 weakens or disappears. What needs further investigation is the exact evolution of the X-ray spectral and jet parameters as this occurs, since at present the most comprehensive studies (e.g., Corbel *et al.* 2002; Gallo *et al.* 2003) are based only on 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 characterize the high/soft state, although often still sub-Eddington (Chen *et al.* 1997). Such high luminosities are, in nearly all cases, very short lived (typically days or less) and the "state" is considerably more difficult to characterize than the canonical low/hard or high/soft states.

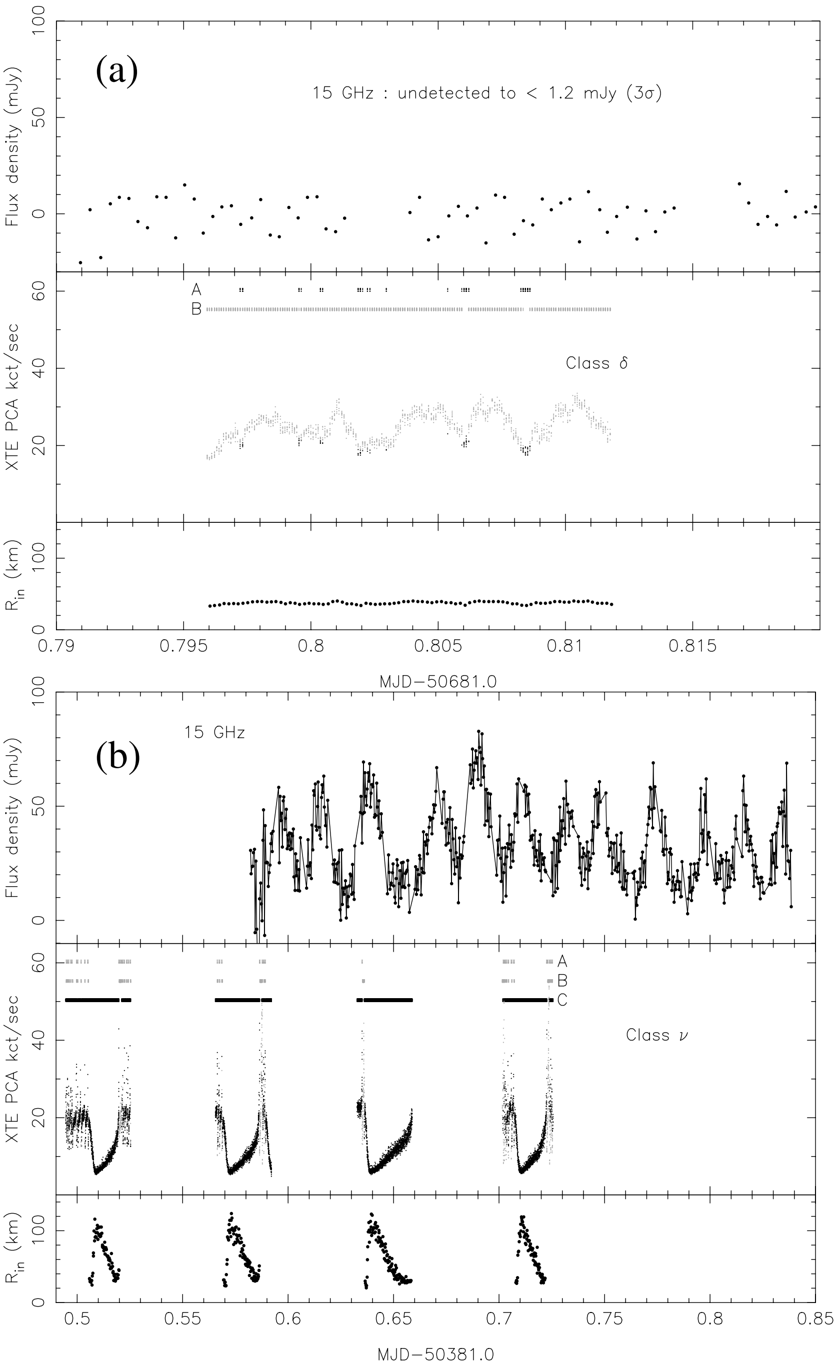


Fig. 9.10. GRS 1915+105 often cycles repeatedly between three X-ray states: A and B are disk-dominated and "soft"; C is much harder (Belloni *et al*. 2000). Panel (a) above shows that when the source only exhibits soft states A and B, the radio emission is very weak; however, when state C is present, Panel (b), 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).

It was 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 polarizations of up to a few $\times 10\%$ have been measured (e.g., Fender *et al*. 1999a; Hannikainen *et al*. 2000), and also circular polarization at the $\sim 1\%$ level (see Section 9.2.6). The broad properties of these transient radio events – i.e., 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 behavior 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 bulk motions (Section 9.2.4). In a comparison of peak radio and X-ray emission from transients, Fender and 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 relatively long orbital periods.

## 9.5 Disk–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.

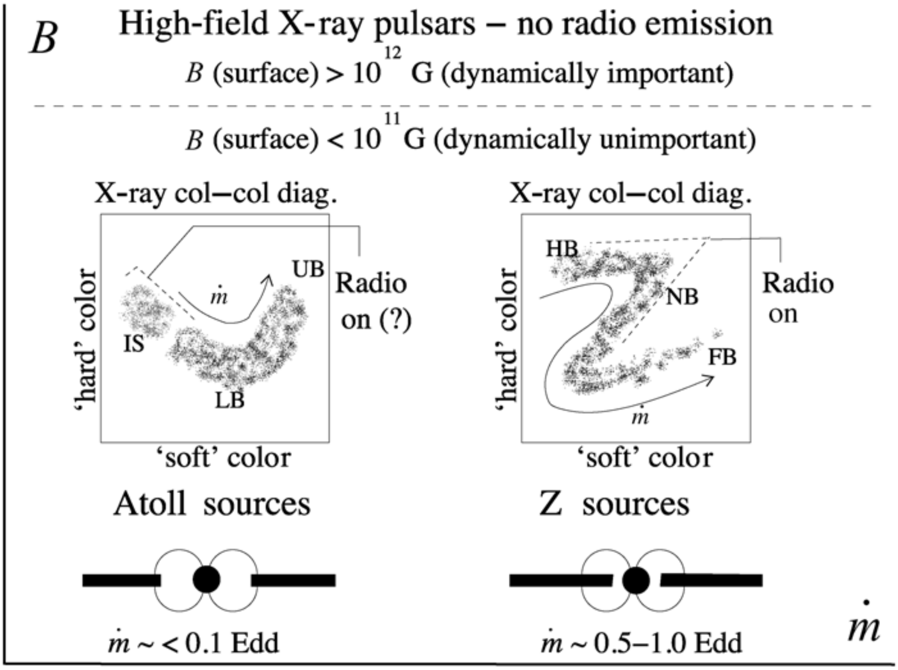


Fig. 9.11. Schematic illustrating our current understanding of the relation between radio emission and X-ray state for the persistent neutron star X-ray binaries.

### *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 behavior (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 *et al.* 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 behavior for GX 17+2 and Penninx (1989) suggested that all Z sources would display comparable behavior. The same pattern of behavior 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 behavior seems to correlate with position in the Z-shaped track traced out on timescales of hours to days in the X-ray color–color diagram (Section 2.5.2.1; 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 (or at least, state, cf. Section 2.5) 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

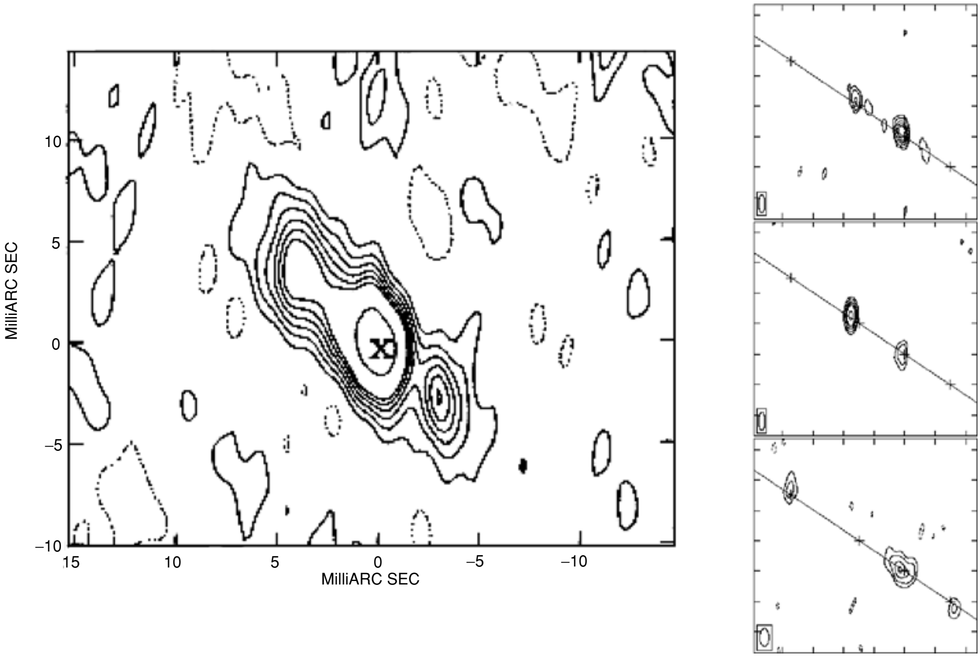


Fig. 9.12. *Left*: A VLBA image of milliarcsecond-scale radio jets from Sco X-1 with the core indicated by X (from Bradshaw *et al.* 1997). *Right*: Multiple sequences of such observations reveal movement of the radio lobes at mildly relativistic velocities ($\sim 0.4c$) while being sporadically energized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

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 sources, 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 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 behavior). 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 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 and 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.; on this issue see also Sections 2.4.2 and 2.5.2.2). Investigation of their disk–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 and 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 "island" (IS) X-ray states (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 disk–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 source states.

#### *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 *et al.* 1990c), the first accretion-powered millisecond pulsar SAX J1808.4–3658 (Gaensler *et al.* 1999) and 4U 1730–335 (The Rapid Burster, Moore *et al.* 2000). To hammer home a point made earlier, I consider 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 is 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 NS transient (perhaps comparable in this respect to the BHC GRS 1915+105 and to Cyg X-3, whose nature is uncertain); 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 arcsecond-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 and Kuulkers (2001) have found that defining a quantity "radio loudness" as the peak radio flux of transients, divided by their peak X-ray flux, *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, Fender & Hendry (2000) found a similar difference. In both classes of object, black holes seem to be 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 (presumably, the black hole spin) in the black hole systems (Fender & Kuulkers 2001). A further possibility (Heinz & Sunyaev 2003; Merloni *et al.* 2003; Falcke *et al.* 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 recent 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 (some 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 *et al.* 2001; Vadawale *et al.* 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 Chandra imaging has unambiguously detected both thermal/emission line (Migliari *et al.* 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 Comptonization (Chapter 4 and, e.g., Poutanen 1998 and references therein; for more detailed

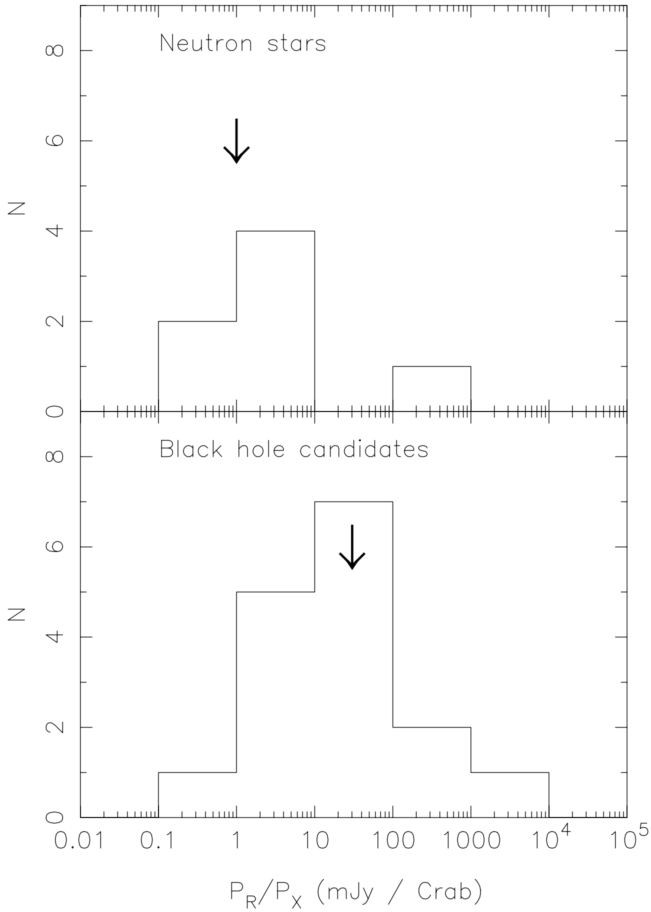


Fig. 9.13. Histograms of the "radio loudness" of neutron star (*top*) and black hole (*bottom*) transients. The black holes are significantly more "radio loud" than the neutron stars, by one to two orders of magnitude. Also indicated by arrows are the mean "radio loudnesses" of the neutron star Z sources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

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 is not therefore an explanation for the extended X-ray jets observed from XTE J1550–564 and SS 433 (Fig. 9.14). Vadawale *et al.* (2001) have suggested that some component of the X-ray spectrum of GRS 1915+105 may arise in synchrotron emission. Georgonapoulos *et al.* (2002) have suggested that X-ray emission may originate due to Comptonization 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 few 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 similar to known "off" state spectra (for XTE J1550–564 and 4U 1755–33) may be associated with beamed, long-lasting jets is of considerable interest.

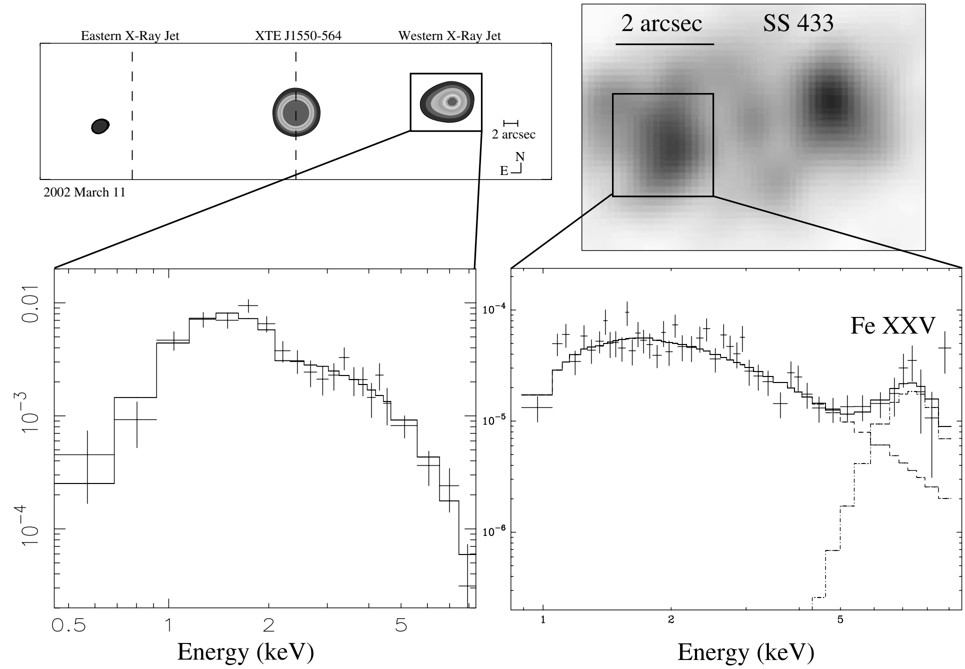


Fig. 9.14. Spatially resolved X-ray spectra of X-ray jets from the black hole transient XTE J1550–564 (*left*) and the persistent powerful jet source SS 433 (*right*). Note the strong emission line (probably Fe XXV) in the SS 433 spectrum, which is clearly not present in the jets of XTE J1550–564. Observations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

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 *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 gamma-ray source. Their favored scenario is that relativistic electrons in the jet Comptonize 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 and 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 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 and 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 $^7$Li – Martin *et al.* 1994; cf. Chapter 5). A possible explanation for the $^7$Li production is spallation in the companion star atmosphere due to the collision of a misaligned jet (Butt *et al.* 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 of both the radiation we observe and the internal physics of 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 *et al.* 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 milliarcsecond-scale jet from Cyg X-1 (Stirling *et al.* 2001; Fig 9.6), arcminute-scale ($\equiv$ 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. 9.2, 9.5). Similarly, a one-sided highly relativistic jet from Cyg X-3 on milliarcsecond-scales (Mioduszewski *et al.* 2001) seems to become a slower-moving, two-sided jet on arcsecond-scales (Martí *et al.* 2001), indicating a deceleration and *in-situ* particle acceleration.

In Sco X-1, the prototype of the Z sources, which are the brightest "persistent" neutron stars, 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

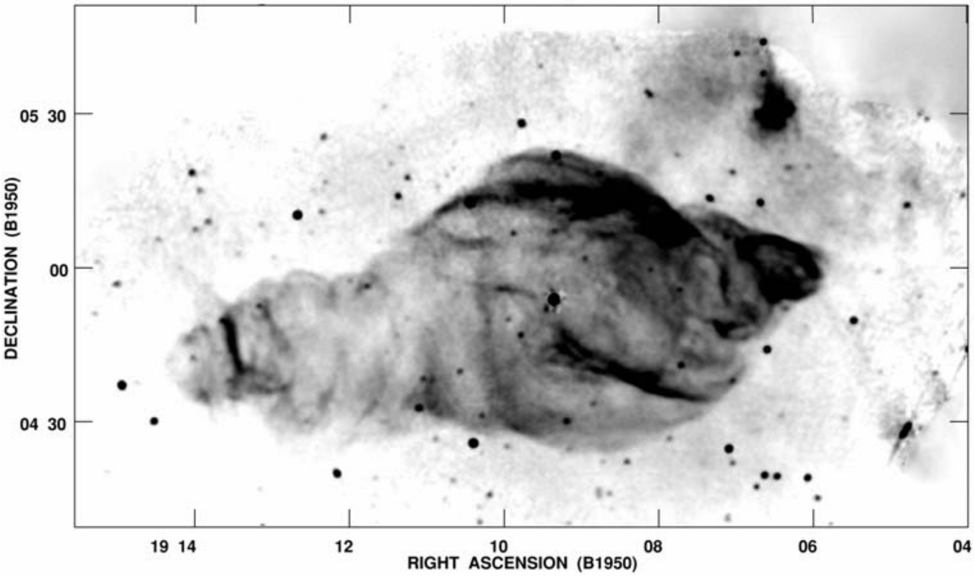


Fig. 9.15. The W50 nebula surrounding the powerful, quasi-continuous jet source SS 433, which seems to have been distorted by the action of the jets over thousands of years. From Dubner *et al.* (1998).

core at mildly relativistic velocities. The recurrent neutron star transient Cir X-1 is associated not only with an asymmetric arcsecond-scale radio jet but with an arcminute-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 *et al.* 1996). Note that on smaller arcsecond, 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 followed 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 disk–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 Chapter 10 by Kuulkers *et al.*). In the following I shall briefly compare X-ray binaries to other jet-producing systems. Figure 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 *et al.* 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 *et al.* (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 disk–jet coupling observed in GRS 1915+105 (Pooley & Fender 1997; Eikenberry *et al.* 1998a; 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 lightcurve – may also have an analog in AGN: Marscher *et al.* (2002) have reported qualitatively similar behavior 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 *et al.* 2003; see Fig 9.9) may be directly relevant for the disk–jet coupling in AGN. Merloni *et al.* (2003) and Falcke *et al.* (2004) have both reported a "fundamental plane" of black hole activity describing the three-way correlation between mass, jet power and accretion power. This plane matches almost perfectly with the Gallo *et al.* (2003) relation between jet and accretion power 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 current observations allow that X-ray binary jets may on occasion achieve 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 behavior 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 non-relativistic jets associated with accretion in (at least) young stellar objects (YSOs; e.g., Lada 1985; Reipurth & Bally 2001) and super-soft sources (SSS; see Chapter 11 by Kahabka and van den Heuvel 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 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 and Kenyon (2003) have reported a possible disk–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).

A conclusion that has been drawn from the comparison of X-ray binaries with such diverse galactic objects is that the jet velocity is always comparable to the escape velocity of the accreting object (e.g., Livio 1999; Mirabel & Rodríguez 1999). However, 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 may not be a hypothesis which can be extrapolated to the relativistic regime.

### *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 than 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 for instance an origin in a jet (Körding *et al.* 2002; see also Georganopoulos *et al.* 2002). At the moment the nature of ULXs remains unclear (see more detailed discussion by King, Chapter 13).

An obvious prediction of the jet model would be radio counterparts to such sources, and there is tantalizing evidence that this may have recently been achieved. Dubus and 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 chapter, 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 and 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 $\sim$steady jet formation has been interpreted by Meier (2001) and Meier *et al.* (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 disk. Merloni and Fabian (2002) discuss "coronal outflow dominated accretion disks" in which they balance both accretion and outflow powers. Livio *et al.* (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 *et al.* 2003). Lynden-Bell (2003) discusses the formation by magnetized accretion disks of "towers" that can collimate jets. In all these theoretical models a magnetized accretion flow is the basis of a MHD outflow: given the widespread acceptance of the magneto-rotational instability (MRI) as the origin of accretion disk viscosity (e.g., Balbus & Hawley 1991; Turner *et al.* 2002), this highlights the probably key role of magnetic fields in the coupled accretion–outflow system (see, e.g., Kudoh *et al.* 2002 for a discussion of a possible relation between the MRI and jet formation). Figure 9.16 presents four different configurations of accretion with magnetic fields that may result in jet formation. In a rather different but still magnetically oriented approach Tagger and Pellat (1999; see also, e.g., Varniere & Tagger 2002), in the "accretion–ejection instability" model, have suggested that an instability related to the vertical component of magnetic field in the inner regions of accretion disks 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 *et al.* (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 *et al.* 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; Becker *et al.* 2001; Markoff *et al.* 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, 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."

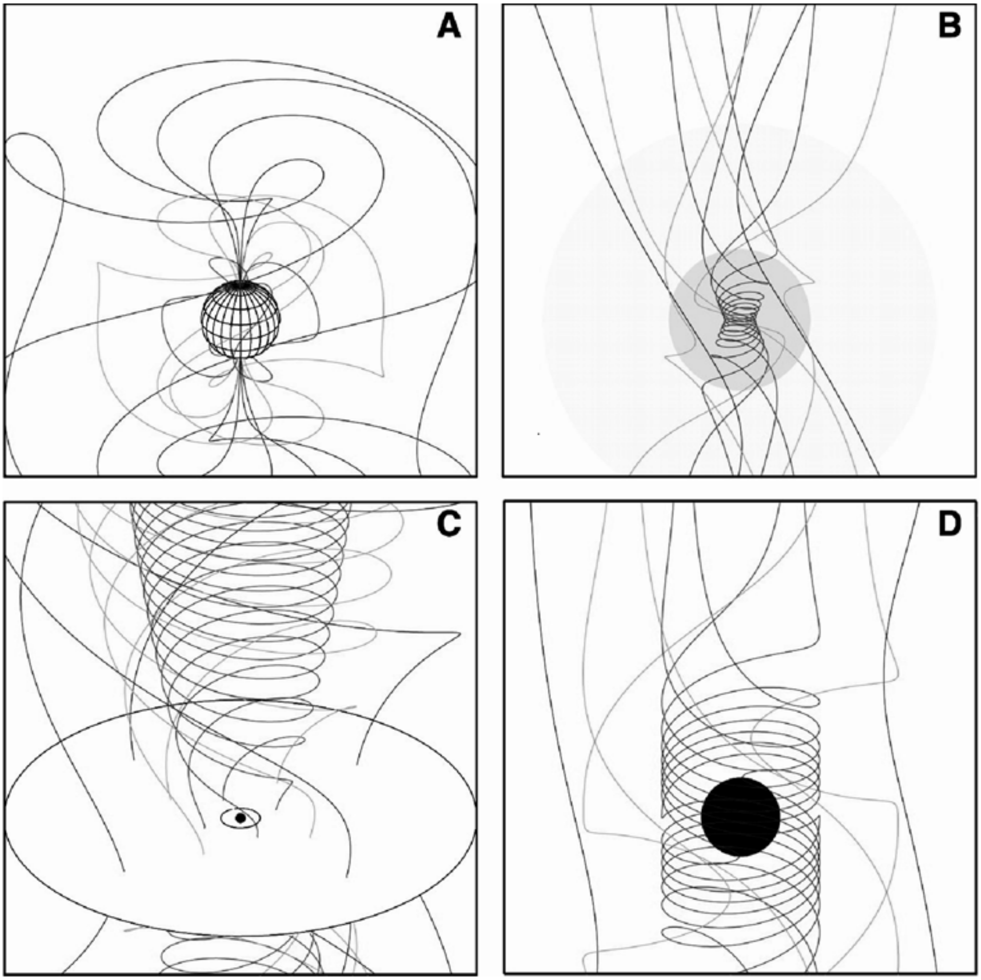


Fig. 9.16. Four ways to make jets with magnetic fields. **A:** dipole field of a rotating neutron star. **B:** A collapsing object drawing and winding up an initially uniform field. **C:** Poloidal magnetic field from a magnetized accretion disk. **D:** Frame-dragging near a rotating black hole resulting in strong coiling of the magnetic field lines. Types **C** and **D**, and 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 *et al*. (2001).

Are we ever going to be able to directly image the jet formation region in X-ray binaries? It seems unlikely – Junor *et al*. (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 Schwarzschild radii), that such imaging will not be possible. For example, a structure of size 100 Schwarschild radii around a 10 $M_{\odot}$ 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 *et al.* (1999) argue that the energy extracted from the black-hole in this way will never exceed that from the inner regions of the accretion disk. 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 (cf. 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 that show a much greater scatter (although this may also be attributed to stronger beaming and less comprehensive coverage of lightcurves – Fender & Kuulkers 2001; Gallo *et al*. 2003). Furthermore, it should be noted that these conclusions are rather contrary to those of Cui *et al*. (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 summarize 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 hundreds 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. I have no doubt that the next decade will provide yet more excitement and surprises in this field. See Fender and Belloni (2004) and Fender *et al*. (2004) for the most recent (i.e. since this chapter was written) developments in the area of understanding the disk–jet coupling.

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