Part II

PERSISTENT AND RECURRENT JETS AND OUTFLOWS

Energetics of jets from X-ray binaries

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

Keywords: black hole physics, neutron star, close binaries, ISM, jet, outflow

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

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

While some areas of the coupling between accretion flow and jet are still empirically uncertain (the Atoll sources, the Intermediate/Very

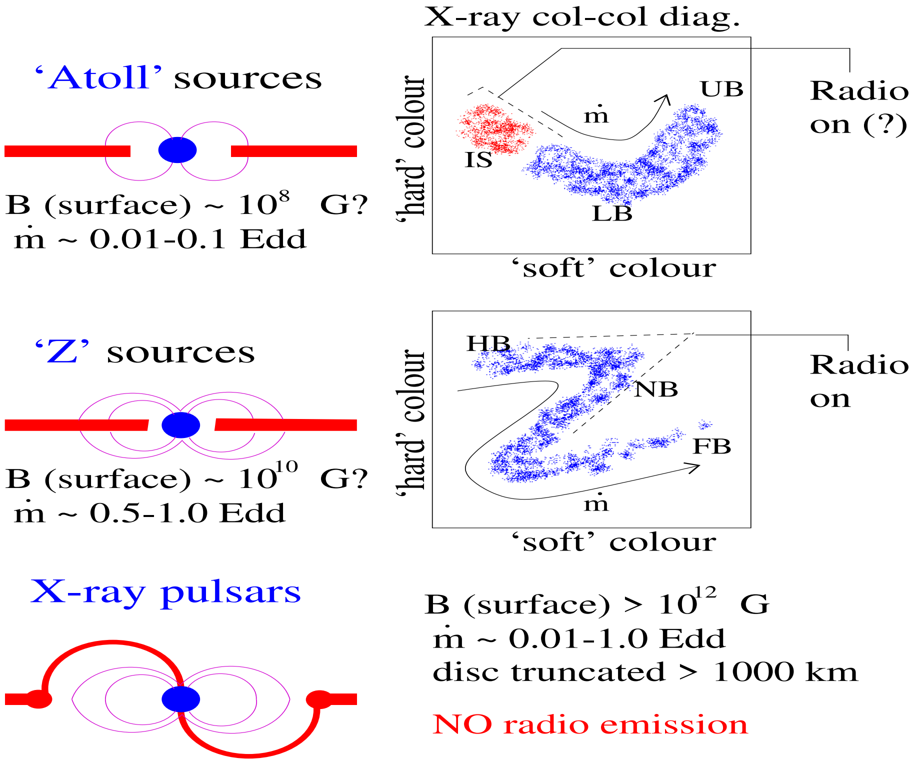

Figure 1. (a): A qualititative sketch of the relation of jets to accretion in the three 'types' of neutron star XRB. In the low-field 'Atoll' sources the accretion rate is believed to be < 10% Eddington, except possibly during rare transient outbursts (e.g. Aql X-1); the evidence is marginal so far but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

High state for BHCs), it seems that all XRBs except the high-field X-ray pulsars will, under the right conditions, produce a synchrotron-emitting jet. It is therefore an important question to address the significance of this jet, energetically and dynamically, for the process of accretion onto compact objects as a whole. One thing obvious from inspection of Figs 1(a),(b) is the apparent anti-correlation between the mass accretion rate, $\dot{m}$, traditionally estimated from X-ray studies alone, and the presence of a jet, in both NS and BHC systems (see also Belloni, Migliari & Fender 2000 and Homan et al. 2001 for further discussion).

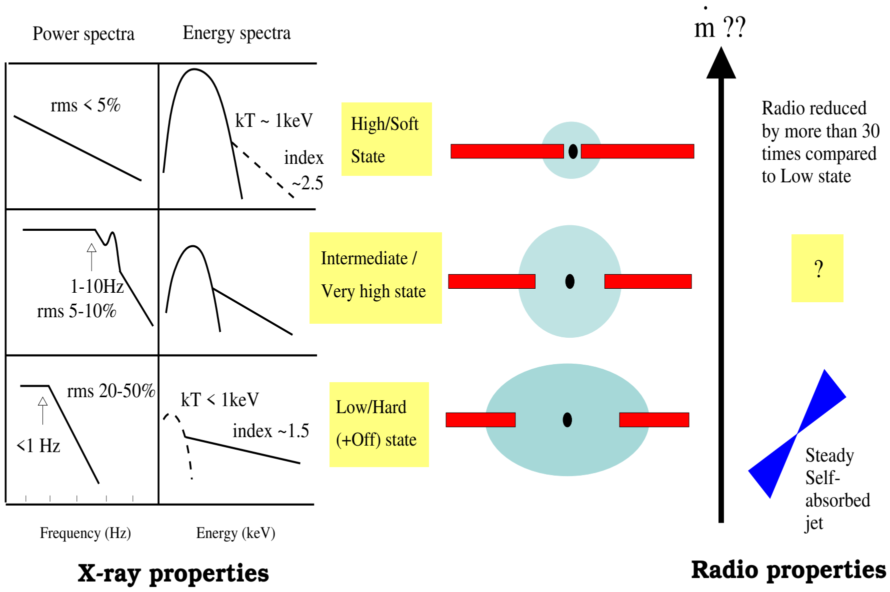

Figure 1. (b): The qualitative relation of radio emission to X-ray 'state' in BHC XRBs: the low/hard state is found to produce a steady, flat- (or inverted-)spectrum jet, the soft state produces no detectable radio emission. The relation of $\dot{m}$ to these states is not certain (e.g. Homan et al. 2001); nor are the radio characteristics of the relatively rare 'Intermediate/Very High' states well determined.

2. Energetics from 'equipartition'

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

One obvious way to associate luminosity and volume is by observing discrete ejection events sufficiently well that the rise time (and therefore maximum volume) and peak flux can be accurately measured. In Fig

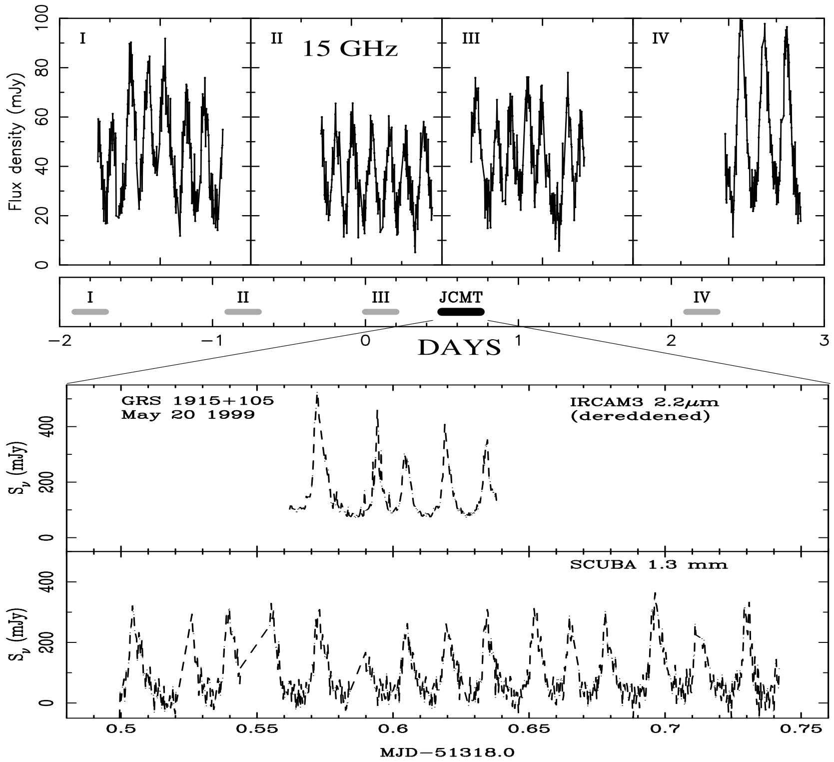

Figure 2. Simultaneous mm and infrared observations of synchrotron oscillations GRS 1915+105 (lower panel). Each event is believed to be associated with a discrete ejection, and the observations came in the middle of a period of more than a week of continuous oscillations as observed at 15 GHz (top panel); see Fender & Pooley (2000). Note that each of the four 15 GHz observations lasts ~ 0.1 hr.

2 we see an example of a sequence of repeated discrete ejection events, observed from radio through the mm band to the near-infrared band. Full details of the observations, and the application of equipartition estimations to these data, are found in Fender & Pooley (2000). The results of the equipartition calculations are presented in Table I. A more basic introduction to minimum energy requirements via equipartition can be found in e.g. Longair (1994).

From the estimates in Table I, it is clear that even in the minimum energy case, ie. a pair plasma with no significant bulk kinetic energy, the power required for the jet is 3×10^{38} erg s^{-1}. The integrated X-ray luminosity (presumably *not* coming from the jet ?) at this time was $\sim 10^{39}$ erg s^{-1}, so we find that even in this case the ratio of jet power to total X-ray luminosity, $P_{\rm J}/L_{\rm X} \sim 0.3$. If we assume that the ejections share the bulk relativistic motion of the major ejections, then it seems $P_{\rm J} > L_{\rm X}$.

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

Case	Γ	L(erg s^{-1})	$B_{\rm eq}$(G)	$E_{\rm min}$(erg)	P (erg s^{-1})	$\dot{M}_{\rm jet}$(g s^{-1})	η
e^+:e^-	1	3×10^{37}	40	4×10^{41}	3×10^{38}	–	< 0.1
e^+:e^-	5	4×10^{39}	115	3×10^{43}	3×10^{40}	–	~ 0.15
p^+:e^-	1	3×10^{37}	40	4×10^{41}	3×10^{38}	2×10^{20}	< 0.1
p^+:e^-	5	5×10^{39}	115	1×10^{46}	8×10^{42}	4×10^{21}	< 0.02

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

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

3. Steady jets – energetics from radiative efficiency

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

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

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

3.0. Spectral extent and radiative luminosity

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

In Fig 3 the broadband radio–optical spectra of eight XRB systems in (low/)hard X-ray states is presented; in all cases the spectra hint at an extension of the synchrotron spectrum to the near-infrared or even optical bands. There is a large amount of additional evidence for such a high-frequency extent to the spectrum, each piece of which may be considered 'circumstantial' but when gathered together presents a compelling case (a lot of this evidence is presented in Fender 2000). Note also that observations of GRS 1915+105 (admittedly not a 'typical' system!), such as those shown in Fig 2, unambiguously establish that the synchrotron spectrum can extend to the near-infrared band.

Our best recent case is the low/hard state transient XTE J1118+480, which clearly shows excess emission at near-infrared and probably also optical wavelengths (Hynes et al. 2000) and whose radio spectrum

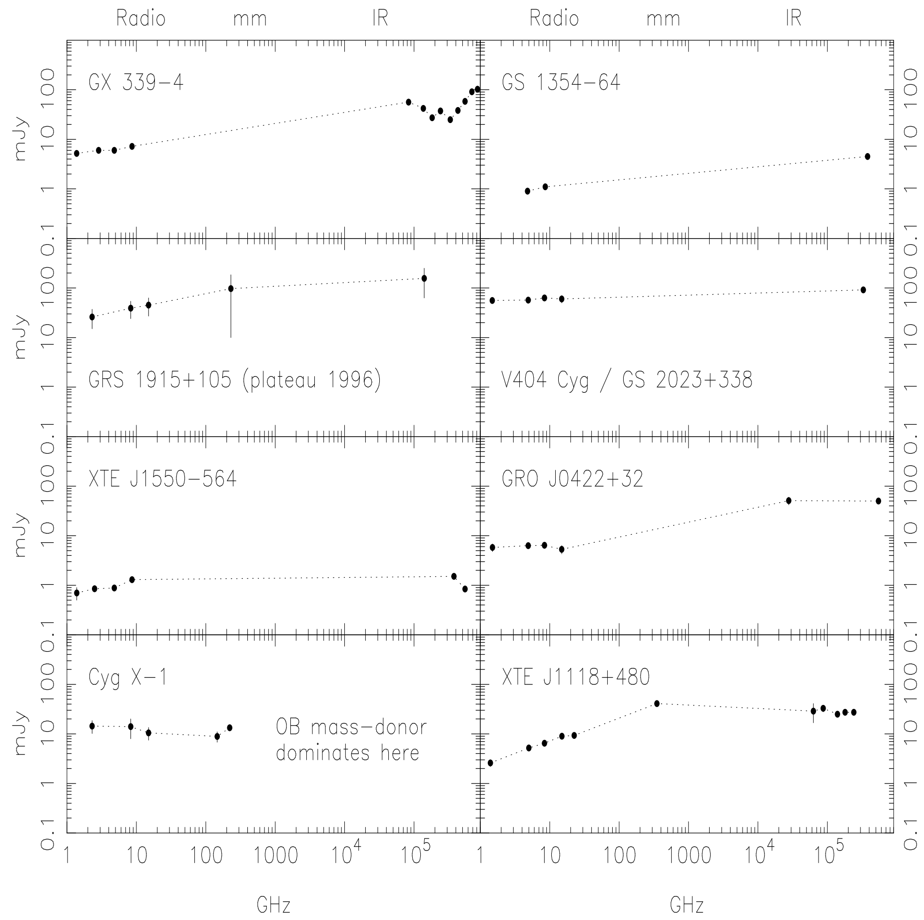

Figure 3. Broadband radio–mm–infrared–optical spectra of eight black hole candidate XRBs in hard X-ray states (apart from GRS 1915+105, all of these can be considered to be the canonical 'low/hard' X-ray state). There seems to be clear evidence in all cases, where observable (ie. not directly in Cyg X-1) for a continuation of the radio–mm synchrotron spectrum to at least the near-infrared band. Data and/or references for all systems in Fender (2000), except GX 339-4 (infrared–optical data from Corbel & Fender 2000), XTE J1550-564 (Corbel et al. 2000) and XTE J1118+480 (Fender et al. 2000).

smoothly connects to a sub-mm detection at 850 μm (Fender et al. 2000). In Fender et al. (2000) it is argued that in this case the synchrotron radiative luminosity is already $\geq 1\%$ of the bolometric X-ray luminosity. How important the total jet power is then depends on our estimates for the radiative efficiency, η.

3.0. Radiative efficiency

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

4. Comparison of jet power to accretion luminosity

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

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

5. Conclusions

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

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

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Radio Jets in LS 5039

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Abstract. LS 5039 is a high mass X-ray binary whose optical counterpart is a bright (V=11) star of O7 V((f)) spectral type, at an estimated distance of 3.1 kpc. The radio emission from LS 5039 is persistent and its radio spectrum is clearly non-thermal. Here we report VLBA and VLA observations which reveal that LS 5039 is resolved into bipolar radio jets emanating from a central core. In addition, this object appears to be associated with one of the enigmatic γ-ray sources detected by EGRET on board the COMPTON-GRO satellite.

Keywords: LS 5039, 3EG J1824-1514, gamma-ray, jet

1. Introduction

It is known that only a small fraction ($\sim 10\%$) of the catalogued X-ray binaries are radio emitters. Some of them are members of the selected class of galactic microquasars, i.e., systems where the radio emission has been resolved into collimated jet structures. During the last years we have been involved in a search for new radio emitting X-ray binaries, looking specially for those with radio jet morphology. The method used for the identification of potential candidates is based on the cross-identification of different radio and X-ray catalogues under very strict selection criteria (Ribó, 2001). The main tools of this search are the NRAO VLA Sky Survey (NVSS) (Condon et al., 1998) and the ROSAT All Sky Survey (RASS) (Voges et al., 1999). After a careful selection process, several candidates were identified. One of them, the star LS 5039, soon focused most of our attention. In a series of VLA observations, LS 5039 appeared as a bright and unresolved radio source, with non-thermal synchrotron spectrum (spectral index $\alpha = -0.5$) and showed some evidences of variability, although with moderate amplitude (Martí et al., 1998). In the X-ray domain, Ribó et al. (1999) reported the absence of any periodic modulation on time scales of 0.02−2000 s and 2−200 d. In this paper, we present high resolution interferometric results on LS 5039 and propose its possible association with the EGRET source 3EG J1824-1514 (Paredes et al., 2000).

2. Milliarc second Radio Jets

The interferometric observations of LS 5039 were carried out with the VLBA plus the VLA[1] at the 6 cm wavelength on 1999 May 8th. The data were calibrated using the standard procedures. The resulting map, uniformly weighted, is shown in Figure 1. This map clearly indicates that LS 5039 is a source of bipolar radio jets emanating from a bright central core. The jets extend over 6 milliarc second on the sky and account for 20% of the total 16 mJy flux density. There is a brightness asymmetry between the jet components, being the south-east component about two times stronger than the north-west component. If we assume this asymmetry to be due to Doppler boosting effects, then a lower limit for the jet velocity ($v \geq (0.15 \pm 0.04)c$) and an upper limit for the ejection angle ($\theta \leq 81^\circ \pm 2^\circ$) can be derived. All these results agree with LS 5039 being a new microquasar.

The radio emission of LS 5039 was at its typical persistent level at the time of our observation and during the weeks before, as inferred from the Green Bank Interferometer (GBI)[2] radio monitoring. The lack of a precursor flaring event suggests us that the jets may be a permanent feature of the source. The size of the emitting region and the observed flux density allow us to estimate a brightness temperature of $\sim 9.5 \times 10^7$ K, indicating synchrotron radiation. By assuming energy equipartition, we estimate a total energy content in relativistic electrons of $\sim 4.8 \times 10^{39}$ erg and a magnetic field of ~ 0.2 G.

3. High–Energy (>100 MeV) γ-ray source

The Energetic Gamma Ray Experiment Telescope (EGRET) instrument on board the COMPTON Gamma Ray Observatory (CGRO) has discovered 271 persistent high energy γ-ray sources (Hartman et al., 1999). However, about 65% of them remain unidentified. We explored

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[2] The GBI is a facility of the NSF operated by NRAO with support from the NASA High Energy Astrophysics program.

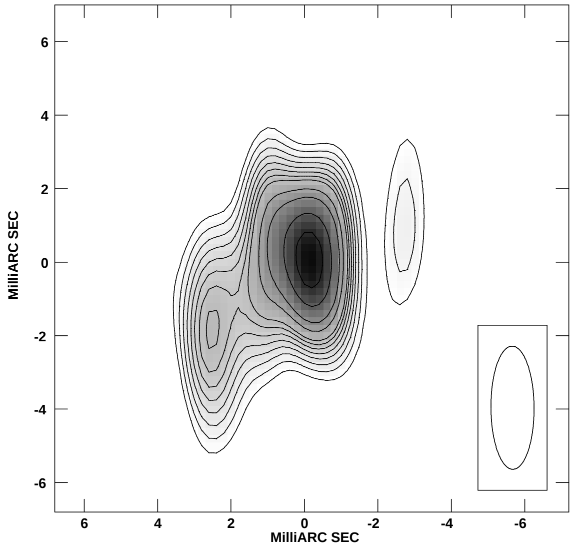

Figure 1. The milliarc sec radio structure of LS 5039 observed at 6 cm with the VLBA+VLA. The contour levels correspond to 6, 8, 10, 12, 14, 16, 18, 20, 25, 30, 40 and 50 times 0.085 mJy beam^{-1}, the map rms noise. The synthesized beam at the bottom right corner is 3.3×1.2 milliarc second^2.

the possibility that LS 5039 is related to one of these unidentified high energy γ-ray source by searching in the Third Egret Catalog. The position of LS 5039 is well inside the 95% confidence contour of 3EG J1824-1514, a persistent source of high energy γ-rays in the Galactic Plane. In addition to the position agreement, LS 5039 is the only X-ray source from the RASS Bright Source Catalog (Voges et al., 1999) within this region of the sky, and is also the only one simultaneous X-ray and radio emitter. The combination of all these clues leads us to propose that the microquasar LS 5039 and the EGRET source 3EG J1824-1514 are very likely to be associated. The supernova remnant SNR G16.8–1.10 is also consistent in position with 3EG J1824-1514 (Romero et al., 1999). In order to study any possible connection between LS 5039 and G16.8–1.10, we have estimated the proper motion of LS 5039 from several databases and our own observations. Our results are consistent with LS 5039 being a runaway star originated from this supernova remnant in a 10^5 yr old explosion.

Figure 2 shows the radio and γ-ray light curves of LS 5039 and 3EG J1824-1514 for the last ten years. Both, the γ-ray and radio emission observed reveal a rather persistent flux. Concerning the origin of the γ-ray photons, it has been proposed that they are created by inverse

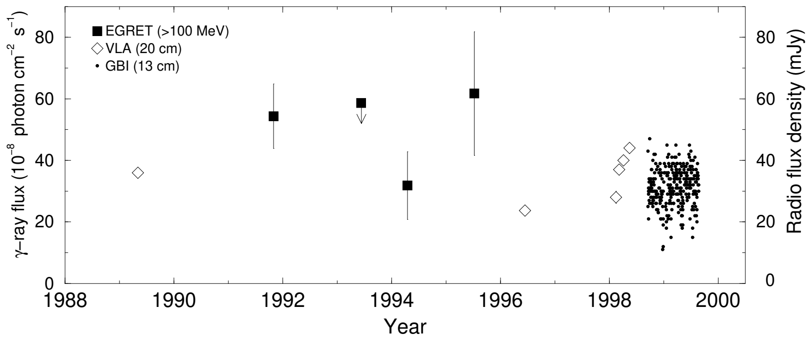

Figure 2. γ-ray and radio light curves of 3EG J1824-1514 and LS 5039. Both sources, with a persistent level of emission, are proposed to be the same object.

Compton scattering of the ultraviolet photons from the hot optical star and the radio emitting electrons. A detailed energetic study can be found in Paredes et al. (2000).

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Internal shock model for the radio emission of Microquasars

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Abstract. The superluminal radio components observed in microquasars are usually interpreted as individual ejection events. We discuss some of the shortcomings of this model and propose the internal shock model in quasi-continuous relativistic jets as an alternative. This model can resolve the problems with the single ejection model and is in agreement with radio observations. We outline some further testable model predictions some of which are already confirmed by observations.

1. The classical 'blob' picture *vs.* the internal shock model

In this paper we concentrate on the most luminous events observed; events A in the scheme of Eikenberry (this proceedings). Since the discovery of superluminal motion in GRS 1915+105 (Mirabel & Rodríguez 1994), the moving radio components were thought of as discrete ejections filled with a relativistic and magnetised plasma. The 'blob' picture is the simplest interpretation of the observations. However, in a detailed comparison of observational data with the predictions of this model several shortcomings become apparent. Firstly, unless it is confined by an external pressure, a blob of plasma will expand freely and in the process its radio synchrotron emission will dim rapidly. Instead, a rather gradual decline of the lightcurves is usually observed. It is of course possible to invoke a confinement mechanism, like the ram pressure of the external medium being pushed aside by the blob, to fit the observations. Nevertheless, this appears to be inconsistent with the observed ballistic trajectories of the blobs. Also, if the blobs are filled with a single population of relativistic electrons, then radiative losses will quickly lead to the formation of a steep spectral break (e.g. Atoyan & Aharonian 1999). With time this break moves to lower frequencies. At a fixed observing frequency we would therefore expect to measure an almost constant spectral index for some time before the spectral break moves below this frequency and the blob vanishes altogether. Instead, a gradual steepening of the radio spectrum is observed (Mirabel & Rodríguez 1994). Finally, the flux ratio of approaching and receding blobs is often found to be inconsistent with the blob model.

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We developed a relativistic version of the internal shock model to apply to the radio observations of microquasars (Kaiser, Sunyaev & Spruit 2000). This model was originally invoked to explain the radio knots in the jets of M87 (Rees 1978) and was later 'rediscovered' for Gamma Ray Bursts (Rees & Meszaros 1994) and blazars (Ghisellini 1999). The basic mechanism is that of a shock, caused by a fluctuation in the bulk speed of the jet material, which travels along a quasi-continuous, conical jet and accelerates electrons to relativistic velocities. In other words, the jet material is moving at a somewhat slower velocity than the shock which overtakes it and 'lights up' the jet.

2. The model in comparison with observations

The shock continuously replenishes the supply of relativistic electrons to the emitting region. The region immediately behind the shock will be brightest. For this region radiative losses are yet unimportant and its luminosity, as it progresses down the jet, decreases because the strength of the magnetic field decreases away from the source centre. Also, the kinetic energy of the material driving the shock is limited and so the shock will eventually weaken. This way, the decline of the predicted radio lightcurve is rather gentle in agreement with observations. The final fading of the radio emission is caused by exhausting the kinetic energy of the material driving the shock.

The accelerated electrons are left behind by the shock and start to 'age' because of energy losses due to adiabatic expansion, synchrotron radiation and inverse Compton scattering of the CMB. In most radio observations the emission regions are not resolved and so a superposition of the radiation from a wide range of electron populations is observed. Starting from the current position of the shock along the jet, these populations were accelerated at successively earlier times and have developed spectral breaks at progressively lower frequencies. Superposition of these spectra results in a composite spectrum which is flat at low frequencies, steepens at higher frequencies where a larger jet region has 'dropped out' and finally cuts off at the frequency corresponding to the highest energies electrons are accelerated to by the shock. This process is illustrated in Figure 1. The whole pattern moves to lower frequencies as time passes and so the model can explain the observed gradual steepening of the radio spectrum.

The region just behind the shock will usually be brightest in this model as here a fresh supply of accelerated electrons is available. So most of the emission of the observed blobs will come from here. This implies that the measured advance speed is that of the shock rather than

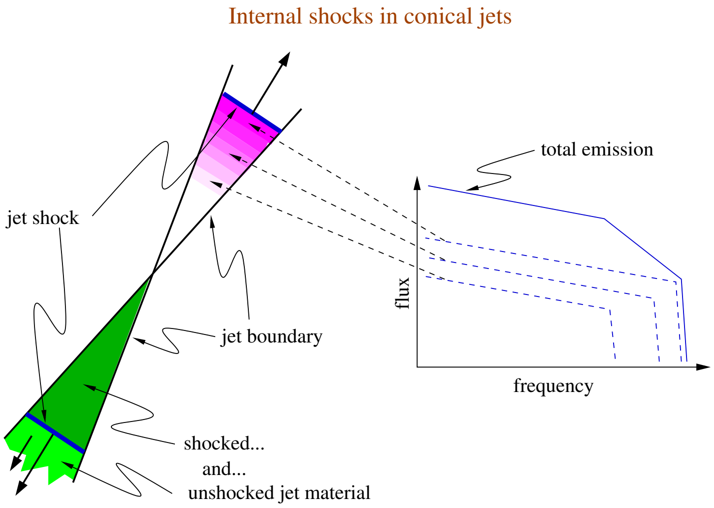

Figure 1. Illustration of the superposition of emission from jet regions of different 'age' (see text).

the bulk velocity of the jet material which is overtaken by the shock. However, the flux ratio of the approaching to the receding jet is set by the bulk velocity of the jet material. This explains the inconsistencies between the observed expansion speeds and the flux ratio.

In Kaiser et al. (2000) we show that the model successfully explains the radio observations of GRS 1915+105 during its radio flare in 1994 (Mirabel & Rodríguez 1994).

The internal shock model can be tested further in various ways. Any moving radio component should show steepening of its radio spectrum towards high frequencies before sharply cutting off. This may be detected in multi-frequency observations. However, limited resolution particularly at low frequencies will always lead to uncertainties whether or not the detected emission is caused by a single shock or is a blend of consecutive shocks in the jet.

The final fading of the radio emission is caused by the shock 'running out of steam'. Less and less electrons are accelerated and so the lightcurve steepens considerably. Because of relativistic effects, this appears to happen earlier in the approaching jet than in the receding jet. The model thus predicts that the flux ratio of the two should change significantly when the lightcurves begin to steepen. This effect may have been observed in a flare of GRS 1915+105 following the famous 1994 event (Rodríguez & Mirabel 1999).

The jet in our model is expanding sideways. Thus the density of the jet material decreases and it should eventually be stopped by the ram pressure of the surrounding ISM. Although the bulk velocity of the jet material is slower than inferred from the measurement of superluminal motions, it is almost certainly supersonic. Therefore, at the end of the jet a strong shock should be formed and the former jet material should inflate a detectable radio lobe as in the extragalactic radio sources of type FRII (Fanaroff & Riley 1974). It has been suggested that the diffuse radio emission region W50 around SS433 is just this lobe (Begelman et al. 1980). Similar structures are detected around other objects (Mirabel & Rodríguez 1999 and references therein).

Simple momentum balance arguments imply that the shock velocity along the jet should be constant (Kaiser et al. 2000). However, in cases when we can observe the shock reaching the end of the jet we would expect a sudden deceleration. For the 'single blob picture' any deceleration should be rather gradual as material is swept up by the blob, unless there is a sudden dramatic increase in the density of the surrounding gas. In the only case any deceleration was ever observed in a microquasar (XTE J1748-288, Hjellming et al. 1999), it was very rapid.

The internal shock model is based on a 'quasi-continuous' jet. In other words, the central engine must produce a jet for some time before the ejection of the material causing the shock. Even without the shock lighting up the jet it is likely that some low level radio emission from at least the inner regions of the jet is detectable. Mirabel & Rodríguez (1999) present high resolution radio maps of GRS 1915+105 during radio quiescence showing an elongated emission region aligned with the axis of the previously observed superluminal components.

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Review on persistent and recurrent jet sources

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Abstract. In this paper I will review the different categories of Jet Sources. These sources can be separated into persistent and recurrent sources, and into extended and compact sources. GRS 1915+105 exhibits properties of both an extended and a compact source. Typically, new results obtained after the Microquasar Workshop in Paris in 1998 will be presented. A large number of these results are a consequence of multi-wavelength observations carried out since the Paris Workshop.

1. 1E 1740.7-2942, GRS 1758-258

1E 1740.7–2942 and GRS 1758-258 are the only two persistent bright sources and persistent hard ($\alpha^{-1.5}$) sources in the Galactic Bulge. Both sources exhibit a core and jet structure in the radio. No optical counterpart has been identified for either source, due to the high extinction, although an F dwarf and an early K giant have been found in the VLA error cycle for GRS 1758-258 (Marti *et al.* 2000a).

Smith, Heindl and Swank (2000) weekly monitored 1E 1740.7–2942 and and GRS 1758-258, and found that each source has a long period (of the order of 500 days) and a short period (over 15 days) which can be interpreted as disk precession and orbital periods respectively. Such long orbital periods imply the need for a giant companion to fill the Roche lobe which could be, for GRS 1758-258 one of the stars seen by Marti *et al.* (2000).

The method used by Smith *et al.* (2000) to extract the short period is to substract a running average from the light curve and perform a Lomb-Scargle periodogram on the residuals. For 1E 1740.7–2942 they derive a slightly broad peak at 12.7 days allowing for a small period derivative. For the GRS 1758-258 the peak is centered at 18.45 days.

Another new interesting result is the recent analysis of a *Chandra* observation of 1E 1740.7–2942 (Cui *et al.* 2000). Using HRGT/ACIS, they discovered a peculiar extended X-ray emission (3" in length), roughly perpendicular to the radio lobe, but surprisingly, no X-ray jets were detected in the 0^{th} order image. Moreover, VLA observations in 1997 of GRS 1758-258 in the hard state show a flat radio spectrum, which could indicate a possible conical jet geometry, related to synchrotron emission of relativistic electrons in an optically thick medium (which will be discussed below) and which can be a signature of a micro-jet.

2. GRS 1915+105

This first galactic superluminal source was recently observed with the VLBA, while the BH binary was in varying X-ray states. It exhibited two different radio states (Dhawan, Mirabel and Rodriguez, 2000): (a) Plateau State, (b) Flare State. The plateau state is characterized by:

- Weak Soft and Strong Hard X-rays (called Hard Low State)
- Radio flux density in the range 10-100 mJy.
- Flat radio spectrum, usually associated with a compact jet (see below).

VLT observations in May 1999 and the use of the ISAAC spectro-imager in July 1999 (Marti *et al.* 2000b) showed that GRS 1915+105 is a high mass X-ray system with an early type primary, as proposed by Chaty *et al.* 1996 and Mirabel *et al.* 1997. Moreover, due to its P Cygni profiles characterised by blue emission wings when the system is bursting, GRS 1915+105 must be surrounded by an expanding envelope. During the flare state, optically thin ejecta (up to 1 Jy) are expelled to thousands of AU (Dhawan *et al.* 2000), whereas during the plateau state, optically thick ejecta, corresponding to a compact jet are expelled from the surroundings of the compact object. GRS 1915+105 is therefore the first source having both: compact and extended jets. This is a major result for the understanding of the compact objects and accretion disk instabilities. We must point out that absorption lines have been seen in GRS 1915+105 spectra (Doppler shifted He-like Fe edge) as well as in GRO J1655-40 (Kotani *et al.* 2000) and could be a signature of superluminal sources.

Concerning the QPOs, GRS 1915+105 exhibits high frequency QPO (67 Hz), usually interpreted as severe effects due to general relativity in the inner accretion disk (Morgan *et al.* 1999) and a low frequency QPO ($\sim 1 - 10Hz$) interpreted by Tagger and Pellat (1999) as an instability occuring in the inner part of the disk. This accretion-ejection instability is responsible in GRO $J16554 - 40$ and GRS 1915+105 for the correlation between the spectral parameters of the inner disk and the QPO frequency (see Psaltis *et al.* 1999, Muno *et al.* 1999, Varniere *et al.* 2000 and Rodriguez *et al.* 2000).

3. XTE J1748-288

XTE J1748-288 was discovered by Smith *et al.* (1998) and its superluminal nature established by Hjellming *et al.* (1998). It presents an interesting example of jet interaction with the ambient medium. The jet slows down considerably at a later stage of evolution and at the same time, the tip of the jet brightens. The enhanced radio emission is probably produced by a shock resulting from the interaction between the jet and the surrounding medium. VLA observations in February 2000 showed a two sided ejection event (Hjellming et al. 2000, in prep). XTE J1748-288 has been observed to brighten and decelarate from 0.93c to 0.23c, probably crashing into the circumstellar matter. Recent observations by ASCA of XTE J1748-288 in a quiescent state (Kotani *et al.* 2000) showed that the jet blob colliding with the environmental matter was supposedly not related to the X-ray source or to the possible presence of a K line from highly ionized iron.

4. Elongated Jets versus Compact Jets

Optically thin medium: Relativistic electrons in a magnetic field in an optically thin medium produce coherent synchrotron radiation, with a radio spectrum with a negative spectral index. The radio emission is usually associated with a high degree of linear polarization. This scenario characterizes extended jets.
Optically thick medium: On the other hand, relativistic electrons in an optically thick medium with a magnetic field produce incoherent synchrotron radiation, whose radio spectral index is flat or inverted, and is associated with a low degree of linear polarization. This is characteristic of compact jets.

The persistent X-ray source GX 339-4 presents X-rays properties usually associated with BHCs. Is it a jet source? Although Fender *et al.* (1997) claimed they could have detected an elongation in the western direction, with the ATCA, there is still a question mark on whether GX 339-4 is a jet source or not. Corbel *et al.* (2000) have shown that there is a clear correlation between the radio and hard X-ray behavior. Moreover, they measured an inverted radio spectrum, with the ATCA, with a radio spectral index = +0.15, corresponding to an optically thick medium and a very small amount of linear polarization, leading to the conclusion that GX 339-4 is a compact plasma jet source (Corbel *et al.* 2000; Fender *et al.* 1999).

5. Cyg X-1 and Cyg X-3

Cyg X-1: GX 339-4 is not the first potential compact source. Cyg X-1 has a flat radio spectrum (Fender *et al.* 2000a), and a similar hard X-ray-radio correlation. VLBA observations of Cyg X-1 (de La Force *et al.* 2000) clearly show a compact jet of about 20 m.a.s extension.

Cyg X-3: Cyg X-3 is also a jet source and VLA observations at 4.995 GHz (Dhawan *et al.* 2000) on April 3, 2000 and April 21, 2000 show a clear jet propagation.

6. SS433

W50 is one of the largest Galactic SNRs and the only one confirmed to harbor a twin jet binary system: SS433. In radio it is elongated in the east-west direction forming the radio "ears".
Safi-Harb *et al.* (2000) pin down the non thermal nature of the X-ray emission of the eastern lobe as synchrotron radiation from highly energetic particles resulting from the interaction between the eastern jet and the SNR shell. Moreover, new X-ray observations of the western jet with RXTE and radio millimeter observations with MOPRA have probed the interaction of the western jet with a dense molecular cloud (Durouchoux et al. 2000). Finally, extended features, though much smaller than for 1E1740-2942, have also been observed in SS433 at radio wavelengths (Paragi *et al.* 1999), as well as circularly polarized radio emission (Fender *et al.* 2000b).

7. Potential new jet sources

*XTE J*1859+226 is a possible eclipsing system due to its long term variation (Chaty *et al.* 2000), with a periodicity of the order of 9 hours. Its spectral energy distribution is best fitted by a (i) simple X-ray heated disk model (ii) viscously heated disk model with an edge temperature of 8000K. Its hard X-ray spectrum and high frequency QPOs make XTE J1859+226 a good BHC.
*XTE J*1118+48 exhibits a periodicity of 4.1 hours. Its spectral energy distribution and mini outbursts in the Low State, make this source an unusual object (Chaty *et al.* 2000). ASCA observations in May 2000 (Yamaoka *et al.* 2000) show: (i) rapid variability in X-rays, (ii) low frequency (0.11 Hz) QPO with a frequency shift (Revnivtsev reported 0.085 Hz a week earlier). A high-brightness core of 1 m.a.s size with an inverted radio spectrum (Dhawan, private communication) makes XTE J1118+48 a potential compact jet source.
XTE J1550–564: Multi frequency radio observations of XTE J1550-564 with MOST and ATCA during the Sept 1998 outburst and associated VLBI observations shortly after a radio flare showed a triple radio structure corresponding to ejections from a jet source (Hannikainen *et al.* 2000). Moreover, a negative radio spectrum index and a small

percentage of polarization (about 6 percent) are good arguments for XTE J1550-564 to be a compact jet source.
SAX J1819.3–2525 is an X-ray transient likely to be associated with the variable star V4641 Sgr. XTE observations of SAX J1819.3-2525 in Sept 1999 showed a flux of the order of 1.5 crab, and a huge H alpha line (6700 km/s) with a blue wing. VLA images obtained on Sept 16, 1999 (Hjellming, 1999) showed an extension of about 0.3" to the North. Moreover superluminal motion was detected after several observations (IAUC 7265). A major question remains: what is the distance of V4641/SAX J1819.3-2525? From radio measurements a distance lower than 1 kpc is derived (making this source the closest radio jet source) whereas a distance greater than 8 kpc is deduced from optical measurements.
LS 5039 is a HMXB with an O7 companion. This source, assumed to be a new micro-quasar system with apparent continuous ejection of relativistic plasma (Parades *et al.* 2000), may be associated with the EGRET source 3EG J1824–1514. VLA and VLBA observations resolved LS5039 into bipolar radio jets emanating from a central core; The jets extend over 6 m.a.s. on the sky and the spectral radio index is negative ($\alpha^{-0.5}$) which corresponds to a non thermal optically thin emission mechanism, implying that LS5039 is a new compact jet source.

8. Elongated SNRs

SS433 is not the only SNR associated with a jet source. A few good examples are listed in SNR catalogs. It is interesting to point out that G54.1+0.3, among few others, has an elongated radio map which fits quite well with the elongated X-ray map (Lu *et al.* 2000). We have found (Durouchoux *et al.* 2000) a molecular cloud in the direction of G54.1+0.3, and CO(1-0) line enhancement at the location of the X-ray hot spot, which could be the signature of the interaction of the jets with a dense medium.

9. Conclusions

Since the last microquasar workshop in Paris in 1998, many new possible jet sources have been discovered. In addition it is now clear that there are two different categories of jets: extended jets, and compact jets. A major result is the radio observations of GRS 1915+105 with simultaneous compact and extended jets. Is GRS 1915+105 a special case or do all jet sources (or superluminal sources) begin with a compact ejection which, in some cases, is tranformed into extended jets? An accurate balance of the jet's energetics associated with numerous new observations could answer this question.

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ISO observations of the Galactic Center Black Hole Candidates 1E 1740.7 − 2942 and GRS 1758 − 258

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Abstract. The Galactic Center black hole candidates 1E 1740.7 − 2942 and GRS 1758 are luminous hard X-ray sources, with $L_x > 10^{37}$ erg s^{-1}. It has been suggested that both of these sources are powered by Bondi-Hoyle accretion from the ambient dense interstellar medium. If this is the case, luminous far-infrared fine-structure line emission should be detectable from both sources. We have obtained *Infrared Space Observatory* observations of both sources and failed to detect emission at the predicted levels, implying that either (1) the hard X-ray luminosities averaged over the last $\sim$ century are considerably lower (by factors of $\gtrsim 3-5$) than presently, or (2) the mass of gas in immediate proximity to the sources is smaller than in the models (which assumed the X-ray sources were embedded in dense ISM) by about the same factor. Option (2) seems more likely, implying that these sources are *not* fueled by Bondi-Hoyle accretion.

The most luminous hard X-ray sources in the Galactic center are 1E 1740.7 − 2942 and the nearly identical source GRS 1758 − 258, with 1 − 100 keV luminosities above 10^{37} erg s^{-1}. Both are also "micro-quasars", with associated time-variable triple radio sources. In addition, 1E 1740.7 was suggested to be the "Great Annihilator" source of narrow, time-variable annihilation-line radiation at 511 keV, a source whose existence now seems unlikely (Malet *et al.* 1995; Purcell *et al.* 1997).

The projected position of 1E 1740.7 − 2942 is directly atop a Galactic center molecular cloud (Bally & Leventhal 1991), while GRS 1758 lies within a few hundred parsecs of the center of the Galaxy. It has been suggested that the prominence of both sources in the X-ray and radio is a result of their embedding in the dense interstellar medium (ISM) of the Galactic Center (Phinney 1992; Chen, Gehrels, & Leventhal 1994), which would also account for the rapid annihilation of the positrons from the Great Annihilator source. This same medium might also power the sources through Bondi-Hoyle accretion, which would require in addition a low velocity of the sources (presumably stellar-mass black holes) relative to the ISM.

If these hard X-ray sources are embedded in dense ISM, then the irradiation of the surrounding gas should produce luminous far-infrared fine-structure line emission, which can be observed in spite of the large visual extinction towards the sources (Maloney, Colgan, & Hollenbach 1997). We obtained *Infrared Space Observatory (ISO)* observations of both sources (Colgan *et al.*, in preparation) which we compare with the model predictions of Maloney *et al.* (1997).

The sources were observed with *ISO* on 22 February and 1 March 1997, using both the Short Wavelength Spectrometer and the Long Wavelength Spectrometer. A number of positions were observed on and around both sources, 10 for 1E $1740.7-2942$ and 18 for GRS $1758-258$ (Colgan *et al.* discuss the data reduction in detail). The interpretation is complicated by the clear presence of unrelated emission in the vicinity of the sources, presumably from photdissociation regions. However, no strong line emission was detected from either source. The upper limits to line emission associated with the compact objects are typically factors of $3-5$ below the model predictions.

This implies either (1) the hard X-ray luminosities of the sources, averaged over the thermal response time of the gas (of order 100 years) are considerably lower (by factors of $\gtrsim 3-5$) than presently, or (2) the mass of gas in immediate proximity to the sources is smaller than in the models (which assumed the X-ray sources were embedded in dense ISM) by about the same factor. (This limit on the gas mass is more stringent than that imposed by the failure to detect fluorescent iron Kα emission at 6.4 keV: Churazov, Gilfanov, & Sunyaev 1996). The latter possibility seems more likely, implying that these sources are not fueled by Bondi-Hoyle accretion from the ISM

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Mid-Infrared observations of GRS 1915+105 and SS433

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Abstract. We have observed in the mid-infrared (4-18 μm) the counterpart of the compact object GRS 1915+105, and the western jet of SS433. The images were carried out with the ISOCAM infrared camera on board of the Infrared Space Observatory (ISO). The mid-infrared photometry of GRS 1915+105 shows the presence of an additional contribution besides the synchrotron emission. The 15 μm images of the large-scale western lobe of the SS433/W50 nebula are compared to the radio and X-ray ones. They show infrared synchrotron emission on the western edge of SS433/W50 lobe.

1. GRS 1915+105

We have imaged the close environment of GRS 1915+105 with ISOCAM at two epochs, on 1996 April 28 and on 1997 October 24. The binary system appears in mid-infrared wavelengths as a faint point source, globally brighter in our 1997 observations than in the 1996 ones. No elongated structure was observed with $1.5''$ pixel field of view, the best ISOCAM resolution. We obtained the photometry with several large-band filters between 4 and 18 μm, and have compared it to simultaneous observations at near-infrared, radio and X-ray wavelengths.

On 1996 April 28 GRS 1915+105 was in a High/Soft state, with nearly constant RXTE/ASM flux (~ 90 counts/s), no significant BATSE flux, and ~ 3 mJy at 15 GHz (Ryle Telescope) few days before and after. On 1997 October 24, 5 days before a major radio and X-ray flare, the compact source was in a plateau state with $\sim$ 50 mJy at 2.25 & 8 GHz (GBI) giving a radio spectral index ~ -0.08, with low constant RXTE/ASM flux ($\sim$ 20 counts/s) and BASTE photon flux ~ 0.06.

The IR data have been de-reddened according to the law from Lutz et al. (1996). We used very simple models combining a hot black body emission or a hot synchrotron one to fit the near infrared data, with a cold black body emission (for a dust envelope heated by the binary) and a synchrotron emission extrapolated from radio wavelengths. We conclude that synchrotron emission alone is not sufficient to explain the mid-infrared flux of GRS 1915+105, and that an additional contribution, which could be dust emission around the binary, is needed.

2. SS433 / W50

SS433 is a high mass X-ray binary surrounded by the supernova remnant W50, a bright radio nebula with a $\sim 1^\circ \times 2^\circ$ unusual ellipsoidal morphology. SS433 produces relativistic jets at subarcsec scales and large scale lobes ($\sim$ 90 pc at a distance of 5 kpc). We have imaged the large scale west radio lobe with the ISOCAM 14-16 μm filter and a $6''$ pixel field of view resolution in September-October 1997.

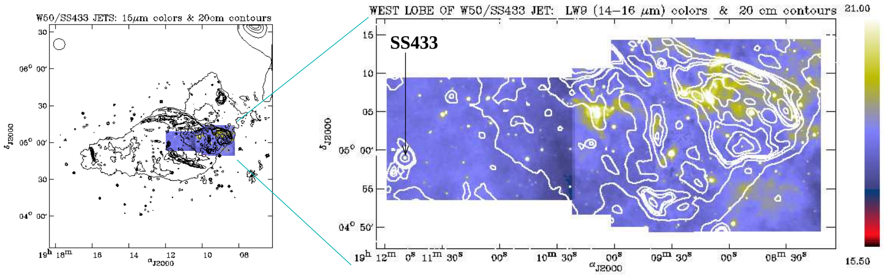

Figure 1. **Left:** SS433/W50 image at 20 cm from Dubner et al. (1998). **Right:** superimposing radio 20 cm contours with ISOCAM 15 μm image shows that the IR emission matches the radio one along the western edge of the radio nebula. **This IR emission is likely to be due to synchrotron radiation.**

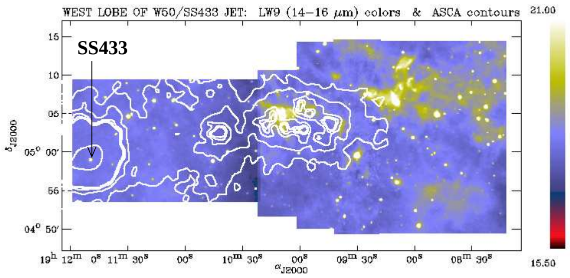

Figure 2. Superimposition of the west lobe X-ray ASCA emission in contours with the 15 μm image in colors. It shows that the IR emission lies along the same axis as the X-ray western lobe. Thus both emissions are the result of the interaction of the mass outflow with the interstellar medium. Most of the IR emission occurs at the western edge of W50 whereas the X-ray lobe fills the space between SS433 and this edge, which is an indication that the jet is present between these two components without being seen (Mirabel & Rodríguez 1999).

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Three modes of long wavelength flaring from GRS 1915+105: implications for jet formation

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Abstract. GRS 1915+105 has exhibited at least three modes of long-wavelength (infrared to radio) flares. Class A flares are the bright (~ 1 Jy) radio events whose apparent superluminal motion in many ways defines the microquasars. Class B flares have intermediate ($\sim 50 - 300$ mJy) flux densities in the IR and radio, and are associated with hard X-ray dipping behaviors. Class C flares are faint ($\sim 5 - 50$ mJy) IR/radio events associated with soft X-ray dips. We discuss each of these classes and their inter-relationships.

Keywords: infrared:stars, X-ray:stars, black hole physics, GRS 1915+105

1. Class A – Large Radio Flares

The discovery of superluminal motions in a radio flare from GRS 1915+105 by Mirabel & Rodriguez (1994) in many ways launched the field of microquasar astrophysics. Such flares have been seen since then (e.g. Fender et al., 1999), and always seem to have peak flux densities of $F_\nu \sim 1$ Jy. The resolved jets with $v = 0.92c$ show spectral evolution from optically thick to optically thin, and seem to recur every few days during an ejection episode. The ejection episodes themselves recur on timescales of a few years. While Harmon et al. (1997) observed an association between the Class A flares and hard X-ray activity, no simultaneous time-resolved X-ray coverage has yet been obtained.

2. Class B – Mid-size IR/Radio Flares

The second class of long-wavelength events were first clearly characterized by Fender et al. (1997), whose same-day IR/radio observations showed flares with flux densities of $F_\nu \sim 50 - 100$ mJy and decay timescales of ~ 10 minutes. The brightness temperature in the radio implied a synchrotron origin for the flares and the constancy of the decay timescale over 4 decades of frequency implied that adiabatic expansion dominates the cooling process.

Eikenberry et al. (1998a,b) observed a long sequence of Class B flares in the IR over two nights in August 1997. These flares had peak flux densities $F_\nu \sim 200 - 250$ mJy and recurrence timescales of $\sim 30 - 60$

minutes. Simultaneous X-ray observations with RXTE revealed that these flares are associated with complex X-ray behaviors (Figure 1). In particular, the flares come after the hard X-ray dips, during which the blackbody temperature in the inner disk drops while the power-law index hardens. Belloni et al. (1997) first interpreted dips such as these as the *disappearance* of the inner accretion disk, and combined with the observations of Fender at al. (1997) and Eikenberry et al., (1998a,b), we recognize that **these events provide the first direct time-resolved observations of relativistic jet formation in a black hole system.**

Mirabel et al. (1998) made simultaneous IR/radio/X-ray observations of several Class B flares, finding wavelength-dependent time delays, with the longer wavelengths peaking later. Such behavior is roughly consistent with that expected from an expanding van der Laan blob, and extrapolations based on this timing would indicate that the ejection occurs near the end of the hard X-ray dip.

3. Class C – Faint Flares

The existence of a third class of long-wavelength flares was first clarified through IR/X-ray observations by Eikenberry et al. (2000). These flares have peak flux densities in the IR of $\sim 4 - 8$ mJy and are associated with rapid soft X-ray dips (Figure 2), during which the blackbody temperature increases and the power-law index softens (as opposed to the hard Class B dips). These flares also seem to explain the quasi-steady IR excess during similar X-ray behaviors in 1997 (Eikenberry et al., 2000).

It is interesting to note that the IR flares appear to begin *before* the X-ray activity, implying an "outside-in" propagation of the disturbance – opposite of the Class B behavior. The spotty coverage from RXTE makes "aliasing" a problem for verifying this. However, Eikenberry et al. (2000) showed that no constant delay fits with the X-rays preceeding the IR flares, and even a non-steady delay would have to reach up to $\sim$ 3000 seconds. Thus, the "IR-first" explanation seems the least objectionable for the observations.

4. Three Separate Behaviors ?

A key issue here is the reality of the distinction between the three classes presented above. The Class C flares seem distinguishable from Class B due to the marked differences in their corresponding X-ray behaviors (soft versus hard dips, IR-first versus X-ray-first), as well as differences in recurrence times and amplitudes. Class B flares, on the other hand, behave in many ways like "baby jet" versions of Class A ejections. In particular, the relative amplitudes and decay timescales are roughly consistent with identical ejections, but with ~ 1000 times less mass in the Class B events. However, Dhawan et al. (2000) have used VLBA to resolve the Class B events, and find that their axis of motion differs significantly from the Class A events. Thus, it appears that there are in fact at least 3 distinct modes of jet production in GRS 1915+105.

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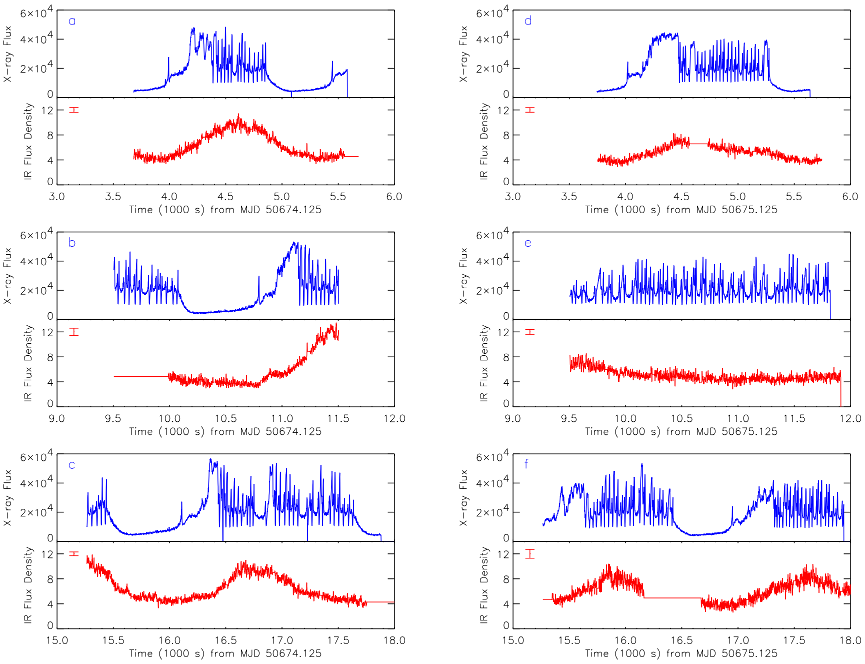

Figure 1. Simultaneous IR/X-ray observations of Class B flares from Eikenberry et al. (1998a).

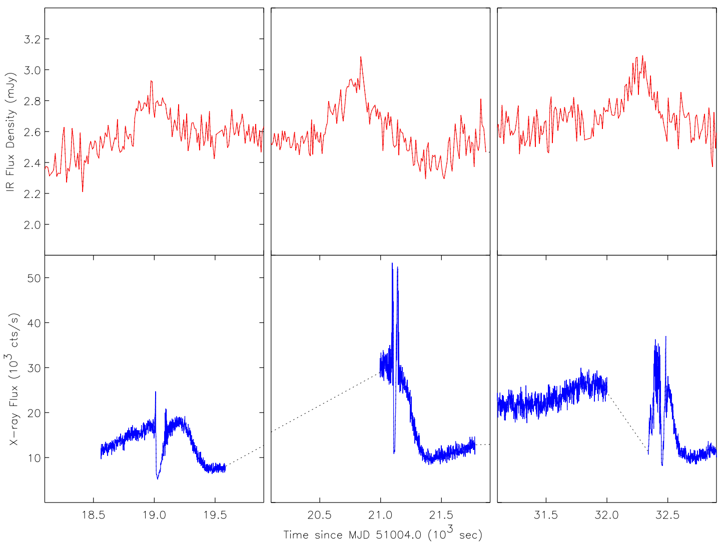

Figure 2. Simultaneous IR/X-ray observations of Class C flares from Eikenberry et al. (2000).

K band monitoring of GRS 1915+105 during 1999/2000

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Abstract. We report on long-term K band photometry of the galactic microquasar GRS 1915+105 since March 1999. We see variations of more than 1 mag, which are seemingly correlated with variations in X-ray intensity and spectral slope.

Keywords: X-ray binary, GRS 1915+105, infrared observations

1. Introduction

GRS 1915+105 is the prototypical microquasar, a galactic X-ray binary ejecting plasma clouds at v≈0.92 c (Mirabel & Rodriguez 1994). Three different sources of infrared (IR) radiation are expected from a X-ray binary, namely thermal emission from the outer part of accretion disk, thermal emission from the companion star or synchrotron emission from the jet(s). Previous IR observations of GRS 1915+105 include, besides a few single measurements since 1993, some few hrs photometry in conjunction with X-ray/radio measurements (Eikenberry et al. 2000), and a 2 month monitoring in 1996 (Bandyopadhyay et al. 1998).

2. Observations and Results

K band observations have been performed with the 1.55-m telescope of the US Naval Observatory Flagstaff equipped with the 256×256 pixel HgCdTe IRCAM camera during 8–10 day intervals around full Moon. Because the main interest was in the long-term behaviour, "only" about 1–3 observations per month were done, consisting of groups of 3 or 4 individual observations per night. Each group represents a set of coadded integrations with an exposure of 400 sec. In total, observations were performed on 34 nights between 05 May 1999 and 15 Jun 2000.

These observations show GRS 1915+105 to be variable between 12.1 $\lesssim$ K $\lesssim$ 13.7 mag (not extinction-corrected; Fig. 1). Our long coverage allows to search for correlations with other emission characteristics, e.g. the RXTE All-Sky Monitor (ASM) quick-look results provided by the ASM/RXTE team. After selecting those K band observations which

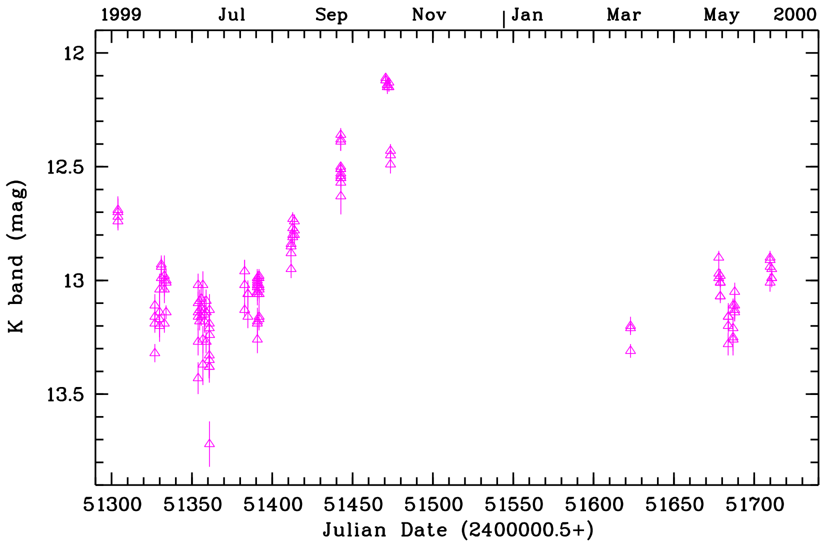

Figure 1. K band light curve of GRS 1915+105, showing the mean of all "groups".

were done within 4 hrs of an ASM scan, we find that both the X-ray flux as well as the X-ray hardness ratio (flux ratio of 5–12 keV vs. 3–5 keV band) are positively correlated with the K band flux.

A regression analysis suggests that a doubling of the X-ray count rate (flux) leads to a 33% increase in the K band flux. This argues against an explanation due to illumination of the secondary. Instead, it rather could be synchrotron radiation related to (small) ejections/flares as seen also at shorter time scales (Eikenberry et al. 2000). In this picture the correlation of the K band flux with the X-ray hardness ratio is compatible with the correlation of X-ray spectral slope and radio flux found by Rau & Greiner (2001). A large (small) value of the hardness ratio corresponds to a flat (steep) X-ray power law slope, and therefore a high (low) temperature of the electrons in the corona if the general comptonization paradigm is adopted. These correlations then imply that strong K band flux and weak radio flux occur during times of a flat X-ray power law, i.e. most of the synchrotron power is radiated either in the infrared or radio band depending only on the temperature of electrons in the corona.

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GRS 1915+105: VLBA Images of the AU-Scale Jet †.

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Abstract. High-resolution observations of GRS 1915+105 are summarized. For full discussion see *Ap.J.*, 543, 1 November 2000; astro-ph/0006086.

Keywords: microquasar, jet, astrometry.

Radio imaging with the VLBA at radio wavelengths (13 cm to 0.7 cm), in different states of the black hole binary, always resolves the nucleus as a compact jet of length $\sim 10\lambda_{\rm cm}$ AU. The brightness temperature of the nucleus is $T_B \sim 10^9$ K, on scales of 2.5 - 7 AU (0.2 - 0.6 milliarcseconds), and its properties are well fit by a conically expanding synchrotron jet model. The nuclear jet varies in $\sim$30 min during minor X-ray/radio outbursts, and re-establishes within $\sim$8 hours of a major outburst, indicating the robustness of the disk/jet system.

At lower resolution (80-240 AU) more extended ejecta are imaged at $\sim$500 AU from the core, with superluminal motion measurable in just hours. The velocity of 1.4$\pm$0.1 c (D/12kpc) for the approaching component is consistent with ballistic motion from 500 AU outwards, perhaps even since birth. The axes of the superluminal ejecta and AU-scale jet differ by $\leq 12^\circ$, and both are stable in time for over 3 years.

Astrometry relative to the extragalactic frame has located the black hole to $\pm$1.5 mas. Its secular parallax, due to Galactic rotation, is 5.8$\pm$1.5 mas/yr, consistent with a 12 kpc distance. A limit of $\leq$100 km/s is placed on its proper-motion with respect to its neighbourhood.

Some black hole systems (e.g. Cyg X-1, 1E 1740-2942, GRS 1758-258, GX 339-4, XTE J1118+48, SgrA*) have compact radio cores with steady, flat-spectrum 'plateau' states, but lack evidence of flares and transient ejecta. GRS 1915+105 is the only source known to exhibit both states.

† We thank the RXTE/ASM team for quick-look results.

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§ Partial support from CONICET, Argentina.

¶ Partial support from CONACyt, Mexico.

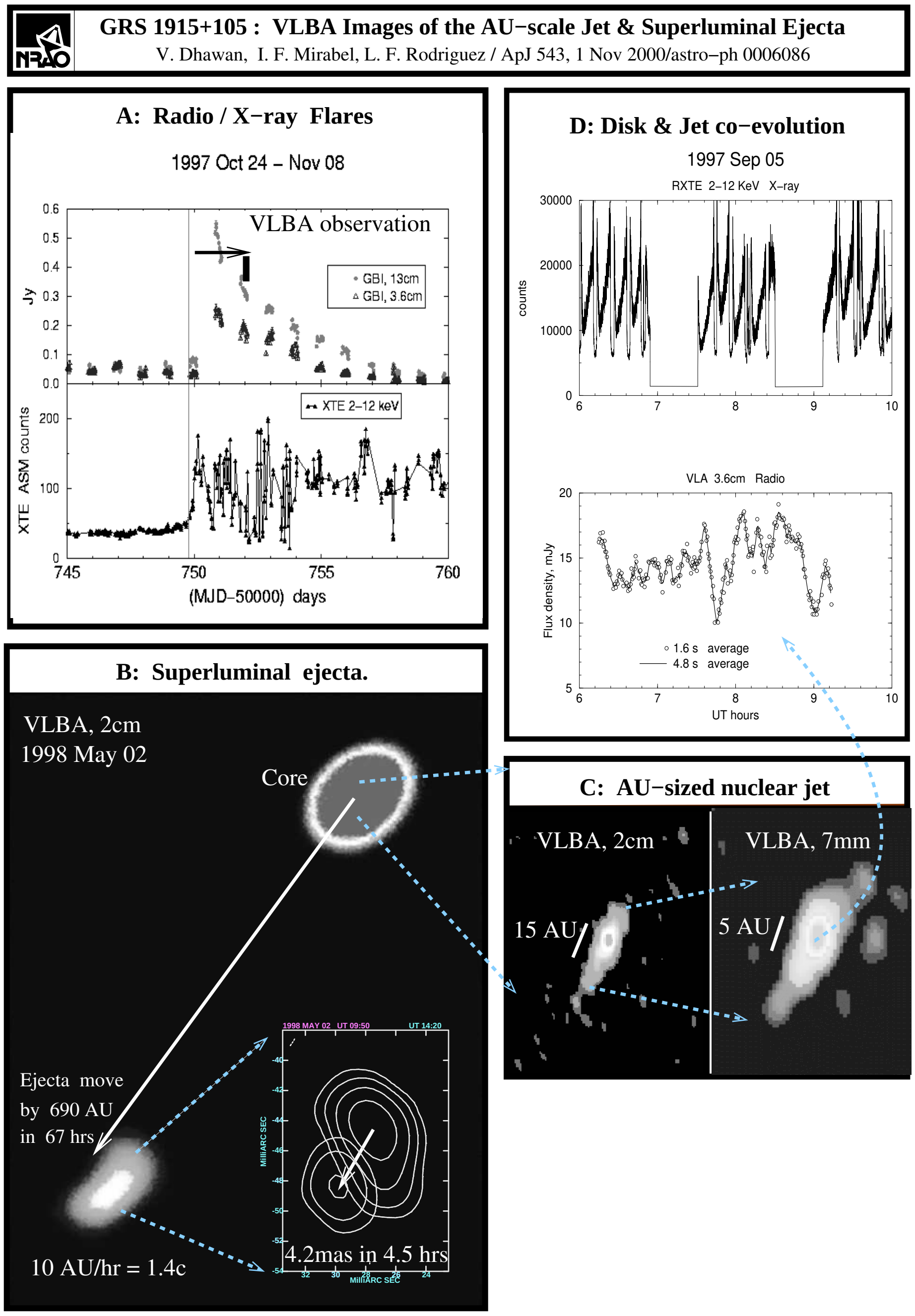

Figure 1. Coordinated X-ray/Radio observations demonstrate Disk/Jet co-evolution.

An attempt to identify the extended synchrotron structure associated with the micro-quasar GRS 1915+105

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Abstract. We used the Effelsberg 100m telescope at 10.45 GHz in attempt to identify extended synchrotron structures formed by jets of GRS 1915+105. For this distant galactic plane source a few suspect structures were pointed out.

Keywords: interstellar medium, jet, microquasar, GRS 1915+105

To plan new observations we analysed a $2° \times 2°$ region centered at the position of GRS1915+105 ($\alpha_{1950} = 19h\ 12m\ 45s$, $\delta_{1950} = 10°\ 51'\ 27"$). At the map composed of the Effelsberg Galactic plane survey at 11 cm superposed on the IRAS 60 μm emission two complexes of HII regions dominate by their strong emission ($\alpha_{1950} = 19h\ 11m\ 47s$, $\delta_{1950} = 11°\ 07'\ 03"$; $\alpha_{1950} = 19h\ 11m\ 06s$, $\delta_{1950} = 10°\ 48'\ 25"$) and the shell-type emission feature near $\alpha_{1950} = 19h\ 14m$, $\delta_{1950} = 11°\ 4'$ is a supernova remnant. Along the jet PA = 155° determined by Mirabel & Rodriguez (1994) three patchy emission features A, B and C were selected, which were not yet identified. We have conducted new observations of these regions at 10.45 GHz. At the map (Fig. 1) the jet position lines given in the literature are plotted (PA = 155° in the middle). In polarization no signal beyond 3 r.m.s was detected.

Source A is a faint extended emission plateau which could be of nonthermal nature. The integrated flux density is about 1.1 Jy. At the bottom of this area a compact source of 99 mJy is visible, coinciding with IRAS 19132+1035 (Rodriguez & Mirabel 1998, Chaty et al. 2000). The sources in regions B and C, outside the range studied by the above authors, are very likely thermal emission features, probably faint HII emission. The 'hot-spot' at the bottom of region B is characterized with a steeper non-thermal spectrum. A map of region C shows an extended source with a thermal-like spectrum. It is characterized with a complicated morphology with a number of brighter spots over the structure. We note that the brightest knots in regions A, B and C are situated close to the GRS 1915+105 jets' axis.

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Figure 1. The total power 10.45 GHz Effelsberg maps of regions A, B and C.

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EVN Observations of GRS 1915+105

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Abstract. New European VLBI Network observations are presented.

Keywords: microquasar, GRS 1915+105

We present new European VLBI Network (EVN) observations aimed at studying GRS 1915+105 at high resolution. TOO observations were performed during gaps in the official observing schedule on 1998 May 31, June 2 and June 9 at 6 cm, 6 cm and 18 cm, respectively. Integration times were of about 4 h in each observation. The telescopes involved in the observations were Medicina, Noto, Effelsberg, Jodrell, Onsala, Westerbork and Torun. The observations at 6 cm were obtained a few days before a major flare (see Fig. 1) while the 20 cm observation was obtained after the radio flare.

In the two images obtained before the major flare, the source is resolved, showing two opposite asymmetric jets (Fig. 2). The main jet is in the SE direction in position angle $\sim 160°$, consistent with the orientation of the main jet present in previous MERLIN and VLA data (Fender et al. 1999; Mirabel & Rodriguez, 1994). The total source extent is of $\sim$13 mas, corresponding to 2.1 $\times 10^{15}$ cm ($\sim$140 AU). The total fluxes are roughly consistent with the Green Bank Interferometry (GBI) fluxes, implying that no large scale structure was missed.

In the third observation, obtained after the flare, the source is unresolved. The total flux is 17 mJy, much lower than the GBI flux. This would imply the presence of extended structure not detected in the present observation, supporting the idea that during the flare strong high velocity components have been ejected.

Assuming that the jets are relativistic and intrinsically symmetric, we can derive an estimate of the velocity from the jet to counter-jet brightness ratio and from the jet length ratio. Using a source orientation to the plane of the sky of 66° (Fender et al., 1999), we derive a range for the velocity of 0.2–0.6c up to a distance of $\sim$8 mas ($\sim$ 90 AU). The absence of visible proper motion between our observations could be due to a continuous ejection in a stable jet.

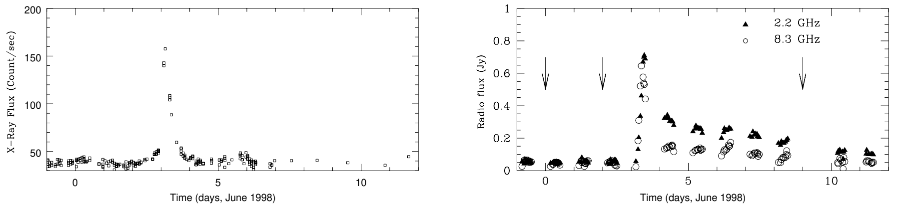

Figure 2. Source light curve in X-rays (RXTE/ASM, left) and in radio (GBI, right), with arrows indicating the epochs of the EVN observations.

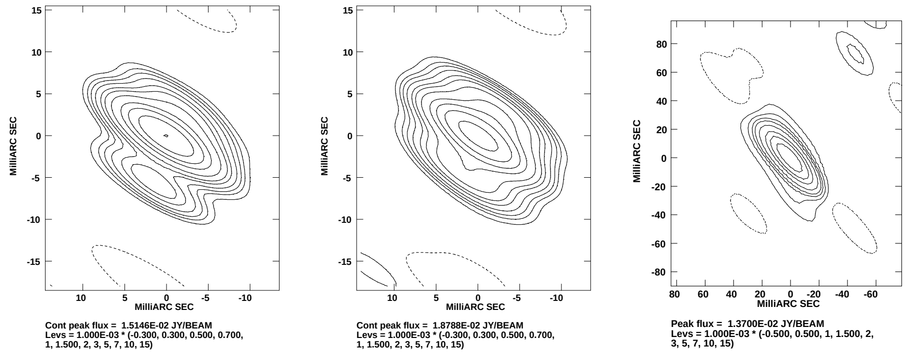

Figure 3. Images of the 3 EVN observations. The first contour is always at the 2σ noise level. Left panel: 1998 May 31, 6 cm, HPBW = $10\times$ 3 mas. Central panel: 1998 June 2, 6 cm, HPBW = $10\times$ 3 mas. Right panel: 1998 June 9, 18 cm, HPBW = $39\times$ 12 mas.

From the present results, it is evident that steady jets exist in the source also before a major flare, in agreement with Dhawan et al., (2000). However a flare produces a strong ejection resulting in extended and relativistic symmetric jets while steady jets are short ($\sim$ 90 AU) and only mildly relativistic (v = 0.2–0.6c).

From the present velocity estimate and the high resolution images obtained by Dhawan et al., (2000) before a major flare, which show a quite symmetric source on a scale of $\sim$50 AU, we find that steady jets appear to accelerate at distance between 50 AU and 90 AU from the black hole as found in a few AGN on the pc scale (see e.g. Cotton et al., 1999; Giovannini et al., in preparation).

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The Accretion-Ejection Instability and a "Magnetic Flood" scenario

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Abstract. I present a global view of recent results on the Accretion-Ejection Instability (AEI), described in more details in other contributions to this workshop. These results address essentially the characteristics of the AEI as a good candidate to explain the low-frequency QPO of X-ray binaries, in particular (at $\sim 1-10$ Hz) of micro-quasars. I then discuss how, if the AEI is considered as the source of the QPO, a possible scenario can be considered where the ~ 30 mn. cycles of GRS 1915+105 are controlled by the evolution of magnetic flux in the disk.

Keywords: accretion, accretion disk, instabilities, MHD waves, galaxies:jets

1. Introduction

The Accretion-Ejection Instability was first described by Tagger and Pellat (1999), based on previous results of Tagger *et al.* (1991). It appears, in the inner part of disks threaded by a vertical (poloidal) magnetic field, essentially as a spiral wave, similar to the ones of galactic disks but driven by magnetic stresses rather than self-gravity. It becomes unstable by extracting energy and angular momentum from the disk, causing accretion, and storing them in a Rossby vortex it generates at its corotation radius (a few times the inner disk radius). The instability occurs if the field has a moderate amplitude (of the order of equipartition), and presents a sufficient radial gradient.

We proposed the AEI as a possible explanation for the low-frequency ("ubiquitous") QPO observed in many X-ray binaries, and in particular in micro-quasars. This is based on the frequency of the instability (a fraction of the rotation frequency at the inner disk radius, as observed), and other properties such as its effect on the disk corona or the fact that, as in galaxies, we expect it to form long-lived, quasi-stationary spiral features, leading to a quasi-periodic modulation of the disk emission. I will present here a global view of recent work, presented in more details in other contributions to these proceedings. I will then turn to the more prospective discussion of a "magnetic flood" scenario for the ~ 30 mn cycles of GRS 1915+105. Starting from the hypothesis that the QPO does correspond to the AEI, we consider various observed properties of the QPO and of the disk, and confront them with what we expect from the AEI. This leads us to this scenario, compatible with known facts, although it cannot be proven at this stage; considered as a possibility, and certainly not as the final word on these cycles, it can thus be used as guidelines for our future work.

2. New Results

2.0. Numerical simulations

We have performed 2D (r, ϕ) MHD simulations of a disk threaded by a vertical (poloidal) magnetic field (Caunt and Tagger, these proceedings). The simulations globally confirm the linear analysis. The instability shows all the expected features (frequency, radial propagation, vortex at its corotation radius, etc.). Non-linearly it saturates at high amplitude, giving a long-lived, quasi-stationary spiral pattern in the disk. Accretion causes the magnetic flux to pile up in the central region, so that most simulations end up with an $m = 1$ (single-armed) spiral, as expected.

2.0. Emission of Alfvén Waves

We have computed the flux of energy and angular momentum "leaking" from the vortex to the corona as Alfvén waves (Varnière and Tagger, these proceedings). A future step will be to determine the way these waves can be damped in the corona, ultimately powering a wind or a jet from the accretion energy.

2.0. QPO Frequency

We expected the frequency of the $m = 1$ mode to be quite sensitive to the rotation profile in the disk. In particular, relativistic effects when the inner radius is close to the Last Stable Orbit allow the presence of an Inner Lindblad Resonance (familiar in galactic dynamics). We have studied this in a pseudo-newtonian potential (Varnière and Tagger, these proceedings). We find that, when the inner radius $r_{int} \lesssim 1.4 r_{LSO}$, an ILR appears and reverses the correlation between r_{int} and the QPO frequency ν_{QPO}.

2.0. Comparison with observations

We have studied (Rodriguez *et al.*, these proceedings) the possibility that this could explain the reverse correlation between ν_{QPO} and the color radius r_{col}, noted by Sobczak *et al.* (2000) in GRO J1655-40 compared to other sources. Comparing with GRS 1915+105, we find that this is a definite possibility, although present results cannot prove it. However a detailed analysis of the data leads to interesting results: 1) In the 30 mn cycles of GRS 1915+105, the QPO appears *before* the dip in the X-ray curve: the QPO might be the cause, and not the consequence, of the transition to the low state. 2) Some data from GRS 1915+105 are compatible with the model of Merloni *et al.*, where anomalously low measures of the color radius result from geometric effects in the disk and corona; but this is not the case in GRO J1655-40, where low radii correspond to high temperatures. It rather indicates that the emitting region is small and hot, *i.e.* that dissipation occurs in a spiral shock or hot point in the disk, which could be a consequence of the AEI.

3. Magnetic flood

These results confirm that the AEI is a good candidate to explain the "ubiquitous" QPO. In order to guide our investigations, we have attempted to go further by considering what this could tell us about the disk. This leads to a "Magnetic Flood" scenario (Tagger, 1999) where the 30 mn cycles of GRS 1915+105 are controlled by the evolution of magnetic flux in the disk.

We start from the fact that a magnetized disk is subject to the Magneto-Rotational Instability (MRI), creating small-scale turbulence, when the field is weak ($\beta = 8\pi p/B^2 > 1$), and to the AEI when it is of the order of equipartition ($\beta \sim 1$). The transition from the high to the low state could thus correspond to a transition between a weakly and a more strongly magnetized configuration, as magnetic flux advected with the gas accumulates in the central region. In a weak field the MRI heats the disk by dissipation of the accretion energy; when the field approaches equipartition the MRI stops and the AEI sets in: this marks the appearance of the QPO, at the end of the high state. The heating of the disk decreases, because accretion energy is redirected to the corona, so that pressure drops and makes β even lower: this would explain why the transition from the high to the low state is so sudden (we note that in recent numerical simulations of the MRI Hawley and Krolik (2000) find that, after some time, the magnetic configuration becomes similar to the one we use here, and most of the accretion energy is carried away by waves. Technically these are fast magnetosonic waves, *i.e.* the same spiral waves involved in the AEI. Although the full 3D treatment limits the spatial resolution of these simulations, we believe that this might very well be a first manifestation of the magnetic flood).

Because of its decreased pressure the disk moves out, and then back in as accretion from outer regions is still going on (the MRI is then seen as the band-limited noise at lower frequencies, corresponding to larger radii; this would explain the correlation between the break and QPO frequencies). The end of the process is marked by a reconnection event (though other large-scale magnetic events could be considered) at the inner edge of the disk, leading to the ejection of a plasmoid and to the destruction of magnetic flux, allowing a return to the high state.

During the low state, some or most of the accretion energy from the inner region of the disk is redirected to the corona. Dissipation of this energy, by a process we still have to work out, would then heat the electrons, leading to the dominant comptonized tail seen in this low and hard state. This would also provide the link between disk accretion and MHD jet models.

This leaves the question of what exists in the region between the disk and the black hole. An ADAF would be possible, but we also consider another candidate: in the Blandford-Zjanek model, the black hole contains magnetic flux due to external currents, held in a force-free magnetic configuration between the black hole and the disk. Such a configuration, containing the magnetic flux advected to the central "hole" in our scenario, would be very similar to an ADAF in many ways: it would form a fat torus of very low density plasma, where the heat exchange time between ions and electrons is much longer than the dynamical time. The inner radius of the disk would be fixed by the equilibrium with the magnetic pressure in the torus.

Although this scenario is still very schematic, it is compatible with the main observed properties of the 30 mn cycles of GRS 1915+105. It leads to a number of questions and prospects: the formation of the compact jet and of the ultra-luminous ejections, the plasma processes in the corona, and the longer term history of this source (which could be compared to other ones) are the most intriguing ones.

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The 1997 hard state outburst of the X-ray transient GS 1354−64 / BW Cir

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Abstract. We present observations of the 1997 outburst of the X-ray transient GS 1354−64 (BW Cir) at X-ray, optical and, for the first time, radio wavelengths. The X-ray outburst was unusual in that the source remained in the low/hard X-ray state throughout; the X-ray peak was also *preceded* by at least one optical outburst, suggesting that it was an 'outside-in' outburst – similar to those observed in dwarf novae systems, although possibly taking place on a viscous timescale in this case. It therefore indicates that the optical emission was *not* dominated by the reprocessing of X-rays but that instead we see the instability directly. While the radio source was too faint to detect any extended structure, spectral analysis of the radio data and a comparison with other similar systems suggests that mass ejections, probably in the form of a jet, took place and that the emitted synchrotron spectrum may have extended as far as infrared wavelengths. Finally, we compare this 1997 outburst of GS 1354−64 with possible previous outbursts and also with other hard state objects, both transient and persistent. It appears that a set of characteristics – such as a weak, flat spectrum radio jet, a mHz QPO increasing in frequency, a surprisingly high optical:X-ray luminosity ratio and the observed optical peak preceding the X-ray peak – may be common to all hard state X-ray transients.

Keywords: accretion, accretion disk, GS 1354−64, black hole candidates, X-ray:stars

1. Introduction

Soft X-ray transients are a class of low mass X-ray binaries in which instabilities in the accretion disc cause a sudden increase in mass accretion rate onto the compact object, resulting in an outburst (see e.g. Charles 1998 and references within). These outbursts are generally accompanied by X-ray spectral softening and we would normally expect the sources to show characteristics of the soft state, as defined by Van der Klis (1994, 1995).

However, this is not necessarily the case and some outbursting systems have remained in the low/hard state throughout the outburst. GS 1354−64 is one such system which entered an outburst phase in 1997

Table I. Comparison between outbursts of Cen X-2, MX 1353−64 and GS 1354−64, which may all be the same source. X-ray peaks are quoted for the 1-10 k eV range. See Tanaka & Lewin (1995) and references within.

Source	Date	Soft X-ray Peak (mCrab)	X-ray State	Optical Peak (mags)
Cen X-2	1966–67	~ 8000	(Very?) high/soft	$V < 13.5$ (WX Cen)?
MX 1353−64	1972	75	low/hard	–
GS 1354−64	1987	≥ 300	high/soft	$V \leq 16.9$ (BW Cir)
GS 1354−64	1997	50	low/hard	$V \leq 17.3$ (BW Cir)

November but did not leave the low/hard state. It is a recurrent transient source which has previously displayed much softer and dramatic behaviour (Table I), if indeed Cen X-2 and GS 1354−64 are the same source (Kitamoto et al. 1990).

2. Observations and results

We have obtained radio data at four different frequencies (ATCA), BVR photometry (0.91 m Dutch telescope, ESO) and public $RXTE$/-ASM, $RXTE$/PCA and $CGRO$/BATSE data for the 1997 outburst of GS 1354−64; the subsequent lightcurves can be found in Fig. 1.

The X-ray lightcurves show well-correlated, triangular-shaped profiles and this observation, coupled with the hard power-law energy spectra, suggests that both hard and soft X-rays are emitted from a similar origin – i.e. the Comptonising corona surrounding the compact object. The energy spectra also show that the soft state was not reached; indeed, the power density spectrum computed from the PCA data shows typical low/hard state temporal properties including a mHz QPO which varies in frequency throughtout the outburst – this frequency variation is also shown in Fig. 1. These X-ray properties suggest a black hole nature for the compact object, although optical observations were insufficient to produce a mass estimate.

The optical lightcurves are unusual for an X-ray transient in that they are not well-correlated with the X-rays and the first optical peak appears to take place ~ 10 days before that of the X-rays. Brocksopp et al. (2000) also find that the optical:X-ray luminosity ratio is surprisingly high – these properties suggest that reprocessing of X-rays is not the dominant source of optical light during this outburst and that instead we see the instability directly as it passes through the accretion disc.

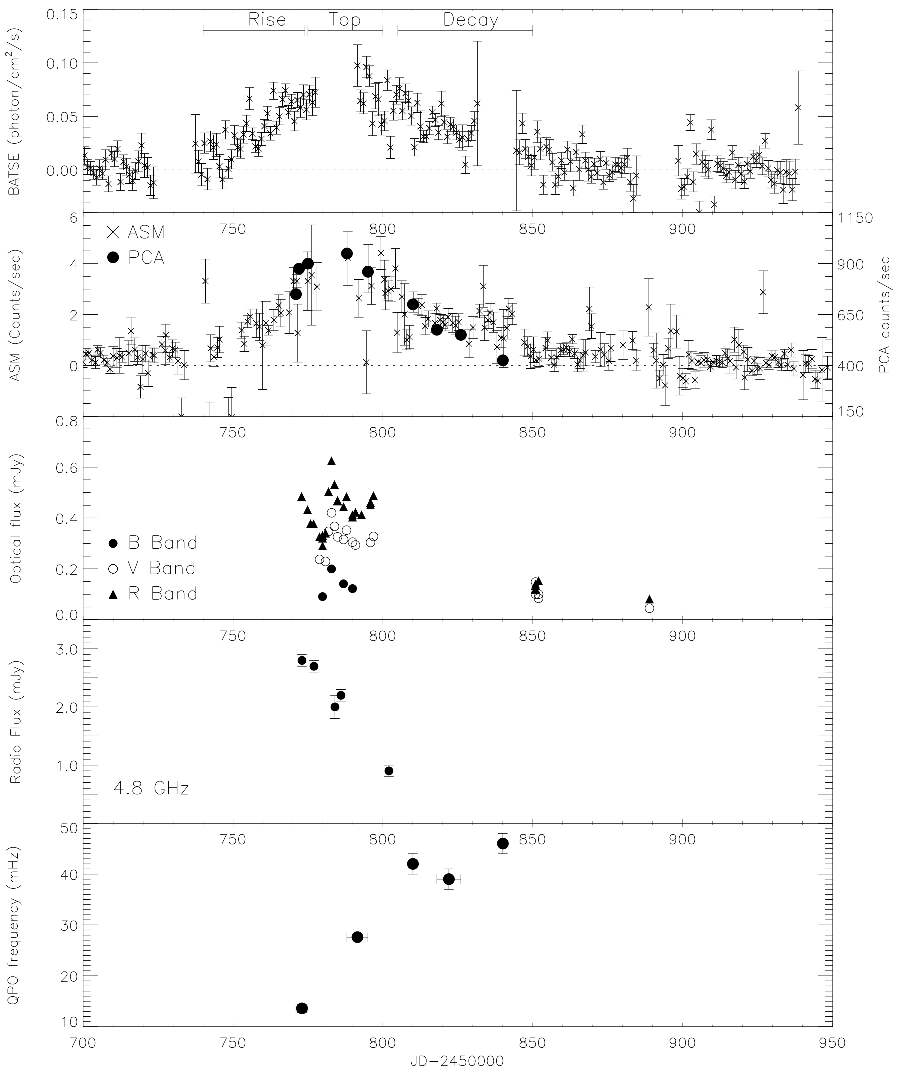

Figure 1. BATSE, ASM, PCA, optical and radio (4.8 GHz) lightcurves of the 1997 outburst for the period 8 October 1997 – 16 May 1998. Radio lightcurves at other frequencies are shown in Brocksopp et al. (2000). Error-bars on the optical points are smaller than the symbols. The variability of the QPO frequency is also shown in the bottom panel.

Our radio observations show that the radio spectrum is flat (i.e. for $S_\nu \propto \nu^\alpha$, $\alpha \sim 0$ is the spectral index, ν is the frequency and S_ν is the flux density at ν in mJy) from 843 MHz, through the radio and into the near-infrared. If it is indeed the case that the radio jet of GS 1354−64 emits synchrotron radiation over such a wide range of frequencies then it must use considerably more accretion power than current X-ray models allow.

3. Discussion

These multiwavelength observations of the 1997 outburst of GS 1354−64 show that we can obtain a wealth of information from outbursts remaining in the low/hard state. Large amounts of X-ray reprocessing dominate the optical outburst of a 'normal' soft X-ray transient and so we are not able to observe the instability pass through the disc – this appears to be possible in a hard state outburst. Likewise, during the soft state the radio jets are quenched and cannot be observed (although radio emission is often observed, probably originating in previously ejected material which then becomes decoupled from the system).

Low/hard state X-ray transients do not appear to be as unusual as once thought – V404 Cyg, GRO J0422+32, GRO J1719−24 and XTE J1118+480 have all entered an outburst phase and remained in the low/hard state throughout. We note that these systems share some of the properties of GS 1354−64 – not only do they show hard state behaviour but they also display a mHz QPO at a frequency which increases during the outburst and a flat spectrum radio jet. Some also show evidence for the 'surprisingly high' optical:X-ray luminosity ratio and preceding optical peak (see Brocksopp et al. 2000 for references). It is probable that some or all of these properties will turn out to be reliable characteristics of low/hard state X-ray transients.

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VLBA Observations of the Super-Luminal Radio Jet from Cygnus X–1 in the Low/Hard X-ray State

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Abstract. We present the detection of a resolved jet–like radio–emitting structure from the black-hole candidate and X–ray binary source Cygnus X-1 at both 8.4 GHz and 15 GHz. The structure in the milli-arcsecond resolution observation with the VLBA at 15 GHz shows an extended emission region to the north–west and possibly also perpendicular emitting regions, believed to be in the orbital plane. This X-ray state is believed to be associated with an advective accretion environment. These observations were spaced 2 days apart over the 5.6-day orbital period. The images confirm the existence of persistent emission from the source from both an unresolved core and a variable, and at least moderately ($> 0.6c$) relativistic jet, during the low/hard X-ray state. However, at this resolution and wavelength they do not show any sign of the emission in the orbital plane observed at a 5σ level at 15 GHz in the initial epoch.

Keywords: X-ray binary, jet, Cyg X-1

1. VLBA and VLA Observation Details

Following the detections of resolved radio structure (Stirling et al., 1998) further high resolution observations of Cygnus X-1 were taken in August 1998 with the VLBA. Three epochs of observations were made every 2 days to cover a large fraction of the period (5.6 days) of the binary system. The runs were made on Aug 10 (Epoch A), Aug 12 (Epoch B) and on Aug 14 (Epoch C) for six hours per epoch. Observations were made at 15.4 and 8.4 GHz, the frequencies being alternated each hour.

Since the source is relatively weak, the phased–up VLA was used as one element of the array, and the high data rate of 256 Mbits per second was used. The observations of Cygnus X–1 (using a position derived from proper motion measurements (Lestrade et al., 1995)) were interleaved with scans on the nearby phase reference source B1955+335.

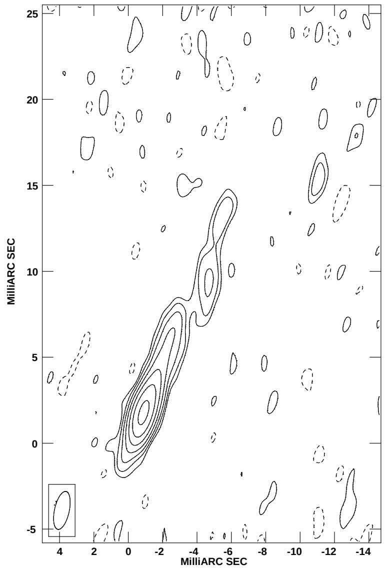

Figure 1. A high resolution image (Epoch A) of Cygnus X–1 at 8.4 GHz; lowest contour 0.15 mJy. Contouring represents a factor of two.

Only the 8 GHz data from Epoch A are presented here; the 8 GHz images and the 15 GHz images and spectral index maps will be published in later papers (Stirling et al. 2000 and de la Force et al. 2001 respectively).

2. Conclusions

A relativistic jet with either a bending flow or a variable ejection angle exists in Cygnus X-1. We cannot confirm or deny the orbital plane emission seen previously at 15 GHz with the 8 GHz images. The unresolved core is likely to have an inverted spectrum, while the extended jets are likely to be optically thin, otherwise the 15 GHz observations should have detected them. It is likely that either self–absorption or free–free absorption occurs near the base of the jets, giving the inverted spectrum. However the optically thin jet contribution will tend to give a flatter integrated spectrum at radio wavelengths.

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VSOP Observations of the X-ray binary LS I +61°303

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Abstract. We present preliminary results from the VSOP observations obtained of a radio outburst of the radio emitting X-ray binary system LS I +61°303. The image shows a central source surrounded by extended emission out to a radius of approximately 2 mas, and spanning along two preferred directions.

1. Introduction

The massive X-ray binary system LS I +61°303 shows regular non-thermal outbursts with a period of 26.5 days (Taylor & Gregory 1982, 1984). Each outburst lasts for about ten days, and seems to be formed by a superposition of different flares, with a rise to the peak flux density over a period of about two days (Taylor & Gregory, 1984; Peracaula et al., 1997).

2. Observations and Analysis

In order to have a dynamical view of the evolution of the radio emitting region of LS I +61°303, the source was observed for 48 hours at 5 GHz, using HALCA and a ground array of 18 radio telescopes, including the VLA, the VLBA and the European VLBI network. In the left panel of Figure 1 the light curve of LS I +61°303, obtained with the Green Bank Interferometer at 8.3 GHz, from about 10 days before to 10 days after the observation, is represented. One cycle of the source periodic radio outburst is visible. As can be seen, the flux density around this peak was very irregular, with variations of the order of several tens of mJy.

In the right panel of Figure 1 we show the image of LS I +61°303 constructed from a 2 hour long segment of data where the flux density was relatively constant. The image shows a central source surrounded by extended emission out to a radius of approximately 2 mas. The extended components seem to span along two preferred directions: NE-SW and SE-NW. The strong variations in the GBI and VLA light

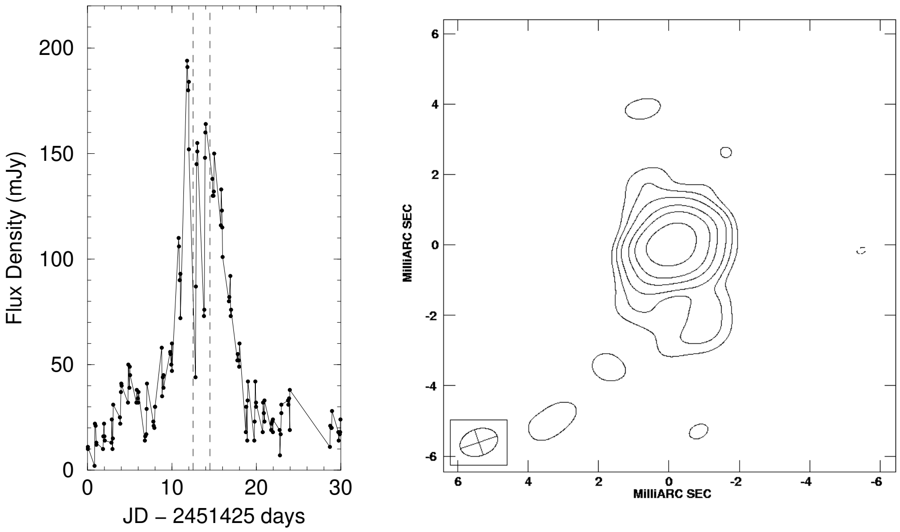

Figure 1. **Left:** Light curve of LS I +61°303 obtained with the Green Bank Interferometer at 8.3 GHz. The dashed lines indicate the interval of time when the VSOP observations took place. **Right:** Image of LS I +61°303 obtained from a 2 hour long subset of the data. Contours are represented at 1 mJy/beam × (-0.5, 0.5, 1, 2, 5, 10, 25). The map peak is 54.3 mJy/beam and the restoring beam FWHM is 1.1×0.76 mas at a PA= -71.2°

curves suggest that we are seeing different flares that could be due to consecutive episodes of particle injection. The remaining data is currently being analyzed to check this hypothesis.

Acknowledgements

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One-sided elongated feature in LS I +61°303

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Abstract. An EVN map of LS I +61°303 presented in Massi et al. (2000) has shown the presence of a south-east extended structure. On the other hand, the measured expansion velocities for radio structures in LS I +61°303 seem small when compared to microquasars. We present here a possible explanation for both such a peculiar morphology and the low expansion velocity in the context of Doppler boosting.

Keywords: LSI +61°303

1. LS I +61°303 in the context of Doppler boosting

LS I +61°303 is an X-ray binary system composed of a neutron star and a B0V star with a stable equatorial disk. It is controversial whether the system belongs to the so called class of microquasars, which have predictable luminosity in the X-ray range and relativistic radio jets.

LS I +61°303 is subluminous in the X-ray range (1–40 keV), having a luminosity of only 10^{35} erg s^{-1}. However, it is the most promising candidate to be the optical counterpart of the γ-ray source 3EG J0241+6103 (Hartman et al. 1999), with a luminosity of 10^{37}erg s^{-1}. Therefore, LS I +61°303 could be another case of X-ray binary having the bulk of the energy shifted from X-ray to γ-ray wavelengths, like the recently discovered microquasar LS 5039 (Paredes et al. 2000).

Several VLBI observations of LS I +61°303 have been undertaken in the past years, which have resolved the source on several occasions showing a structure of a few milliarcseconds (Massi et al. 2000 and references therein). However, the measured expansion velocities apparently contradict the assumption that the outburst is related to super Eddington accretion events (Taylor et al. 1992). The VLBI measurements give an expansion velocity in the range of $(0.001–0.06)c$. As reviewed by Mirabel & Rodríguez (1999), the expansion velocities for microquasars (as SS 433, Cyg X-3, GRS 1915+105, GRO J1655−40) range from $0.1c$ to $0.9c$. The peculiarity of LS I +61°303 is evident. However, we note here that the measured velocity of $(0.001–0.06)c$ is simply the apparent transverse velocity (v_a) and this might not be quite representative of the true velocity (v), especially for small values of the angle (θ) between the ejection and the line of sight.

Massi et al. (2000) performed an EVN observation 10 days after an outburst in 1994 June. The obtained map exhibits an extended structure elongated to the south-east. Assuming the source as a result of an expansion they derived a velocity of $0.004c$, in agreement with the above given range. The best fit of the visibility amplitudes and phases is obtained with a two-component model given by a point source and an elliptical gaussian component with position angle of 123°. In some of the previous VLBI maps one may see extended structures at comparable position angle but not so pronounced. The asymmetry in the EVN map seems that of a one-sided jet typical to those due in the AGN to Doppler boosting. In this context we derive, from the peak value of our map and its noise level, $\beta \cos\theta > 0.3$, where $\beta = v/c$. On the basis of the relationship between apparent speed of the approaching component β_a=0.004 and intrinsic speed β we derive: β >0.39 and θ <0.4°. This lower limit of velocity of LS I +61°303 compares well with the other microquasars. We note that the combination of the values of θ and β we have found gives γ=1.1 and a Doppler factor δ=1.5 for the approaching jet. Finally, the EVN one-sided jet seems to be aligned with a large jet-like structure, located 2' away, present in a deep VLA map. New observations with resolution intermediate between that of the VLA and VLBI are already in progress.

Acknowledgements

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The X-ray Spectrum of the Jets in the SS 433 system using the Chandra HETGS

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Abstract. Observations of SS 433 using the Chandra High Energy Transmission Grating Spectrometer are presented. Many lines of highly ionized elements are detected; all are detectably broadened by 2000-5000 km/s and the widths do not depend significantly on the characteristic emission temperature, suggesting that the emission occurs in a freely expanding region of constant collimation. Line ratios show that the base temperature of the jet is below 10 keV and may be closer to 2.5 keV. The X-ray luminosity during this observation was somewhat lower than average, which may be related to the lower jet temperature. The blue shifts of lines from low temperature gas are the same as those of high temperature gas, indicating that jet acceleration occurs closer to the compact object than $\sim 2 \times 10^{11}$ cm, where the emission lines originate. The image from zeroth order shows extended emission at a scale of $\sim 2''$, aligned in the direction of the radio jets.

Keywords: SS 433, jet, spectroscopy

1. Introduction

The Galactic X-ray binary SS 433 is the only known astrophysical system where red- and blue-shifted lines are observed from high Z elements. Lines from the H Balmer series were modelled kinematically (Margon et al. 1981) as emission from opposing jets emerging from the vicinity of a compact object at $0.26c$ along a line inclined about $80°$ to the line of sight. There are radio jets which are oriented at a position angle of $100°$(east of north) which show an oscillatory pattern that can be explained by helical motion of material flowing along ballistic trajectories (Hjellming & Johnston 1981). The radio jets are about $2''$ long for a linear dimension of $\sim 3.5 \times 10^{19}$ cm, assuming a distance to SS 433 of 3 kpc.

EXOSAT X-ray observations showing that the 6.7 keV line appeared to shift with precession phase were interpreted as detecting Fe XXV from 10 keV gas (Watson et al. 1986). Using Ginga, Brinkmann et al. (1991) concluded that kT was more like 30 keV while Kotani et al. (1996) obtained a value of 20 keV based on the ratio of Fe XXV and Fe XXVI line fluxes from ASCA data.

SS 433 was observed using the High Energy Grating Spectrometer (HETGS) while the compact object was not in eclipse and at a precession phase (0.6) that gives maximal separation between blue and red jets. An example of the high spectral resolution of the HETGS is shown by Canizares et al. (2000). An important feature of the HETGS is that spectra are obtained independently and simultaneously using the High Energy Gratings (HEG) and the Medium Energy Gratings (MEG). The HEG spectra have higher spectral resolution but lower effective area below 2 keV. Details of the spectroscopic analysis will be presented elsewhere.

2. Imaging

The zeroth order image is distinctly elongated in the east-west direction, which is the same orientation as the radio jet. Due to event pileup, we cannot determine if the image matches that of a point source within $1''$ of the core but profiles along the E-W and N-S directions are clearly different, as shown in figure 1. There are "shoulders" on the E-W profile that do not appear in the N-S profile. The total power in this extended component is less than 1% of that in the point source and is detectable out to $5''$ from the core or up to $\sim 3 \times 10^{17}$ cm.

3. Spectra

The X-ray spectra show strong emission lines of H- and He-like ions of Si, S, and Fe due to thermal gas at 3-6 keV and lines of Fe XXIV, Mg XII and Ne X from gas at ~ 1 keV. There are two sets of lines: the blue system has a shift of $v/c = -0.078$ while the red system has a redshift of 0.153. The blue system lines are stronger than the corresponding red system lines, as expected from Doppler boosting. In most of what follows, the emission from the blue-shifted jet is modelled.

The lines are broadened by $\sim$2500 km/s (FWHM) as found in the (optical) H lines. The broadening is consistent with the range of line-of-sight velocities expected from a freely expanding, conical flow. From the FWHM, we infer an opening angle of $\sim 2^\circ$. The redshifts of the He-like (resonance lines) and the H-like lines are identical, indicating uniform jet outflow because the bulk of the S XVI flux originates in hotter material closer to the jet base than the Si XIII flux – thus, we do not detect the jet acceleration zone. The line broadening is similar for all lines, indicating that the jet opening angle is the same for all line emission – thus, we are not detecting a "nozzle" of expansion at the jet base. If the emitting plasma were entrained along the surface of a much faster jet, one might expect a "hollow cone" geometry that would give rise to double-peaked emission lines which we do not observe. Thus,

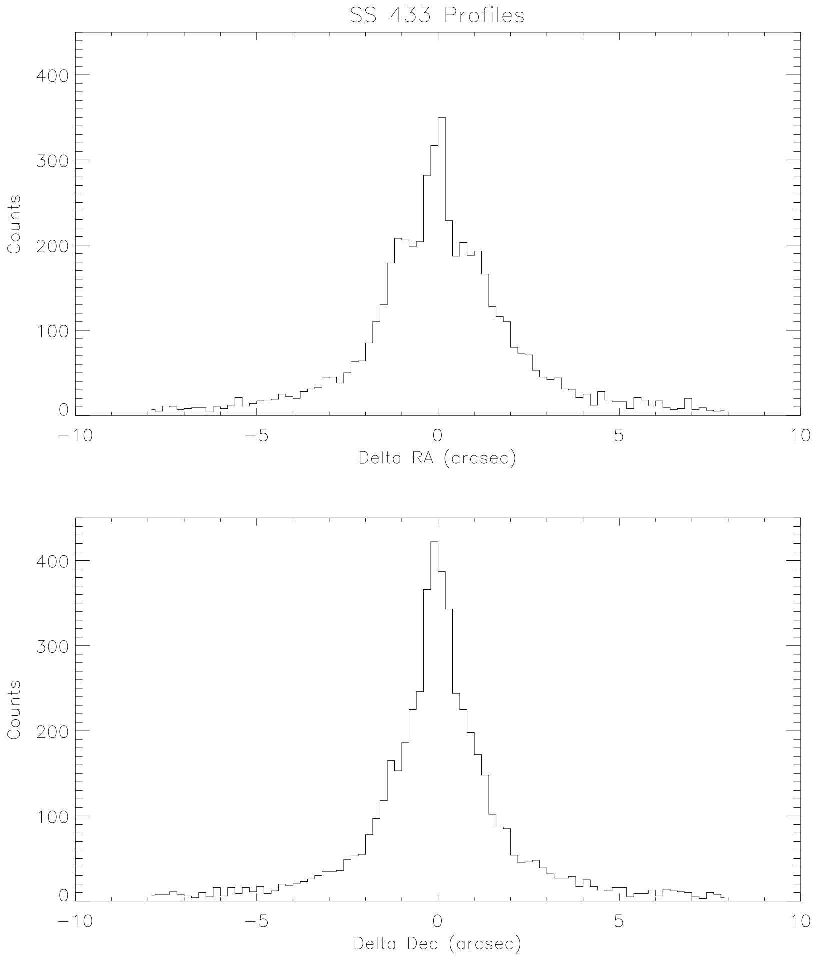

Figure 1. One dimensional image profiles of the zeroth order image of SS 433. *Bottom:* Profile along the north-south direction. The image is affected by pileup so the shape is not consistent with a Gaussian. *Top:* Profile along the east-west direction. The image is distinctly different than the north-south profile due to emission from a 1-2″ scale jet.

the cone is filled; i.e., the heavy elements are mixed into the bulk flow of the jet.

The flux ratios of the Fe, S and Si H-like to He-like lines gives temperature estimates near 2.5 keV. The Fe XXVI (H-like) line is too weak to allow temperatures in excess of 10 keV for emission measures comparable to that required for the Fe XXV line. The resonance to intercombination and forbidden flux ratio gives a similar temperature estimate for these ions.

A multi-temperature model of the combined spectra indicate that the Si XIII emission originates in gas with a temperature of order 1×10^7 K. The Si XIII forbidden lines are somewhat blended with the broadened resonance lines but are discernably weaker, indicating that the plasma density is high. Based on Gaussian fits to the lines in the triplet, we estimate that the electron density is $\sim 3 \times 10^{13}$ cm^{-3}. The total flux of the Si XIII lines and the estimated distance give us an estimate of the emission measure, assuming a filling factor f. For the Si XIII line, we find an emitting volume of $\sim 10^{34} f$ cm^3. Given the line widths and an assumed conical geometry, this volume corresponds to a distance from the core of $2 \times 10^{11} f$ cm, which much smaller than the size scale of the radio and extended X-ray jets.

Although a simple absorbed power law gives a good fit to the continuum, it is dominated by bremsstrahlung from the same thermal plama that produces the emission lines. Thus, we find no evidence for nonthermal emission from the central source.

4. Conclusions

The X-ray spectrum of SS 433 was used to place constraints on the the acceleration of the material in the jet: it appears to arise in a center-filled cone with constant opening angle and constant flow velocity. For one temperature zone, the density is high enough to suppress the forbidden line and can be used to estimate the distance of the emission from the core.

Acknowledgements

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Radio properties of the compact jets and the Equatorial Emission Region in SS433

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Abstract.
Results from multi-frequency VLBA experiments and a 1.6 GHz global VLBI observation of SS433 in 1998 are briefly summarized.

1. The compact jets of SS433 and RJXRBs

The innermost radio jets in SS433 are quasi-continuous, rather than knot-like (Vermeulen et al., 1993). Within this compact jet region ("core-wings") there is a ∼25 AU central gap, which harbours the binary stellar system (Paragi et al., 1999). The existence of this Central Radio Gap is confirmed in our VLBA monitoring experiments in 1998. Its size decreases slightly with observing frequency (7–8 mas at 5 GHz, 5–6 mas at 15–22 GHz), and depends on the precessional phase as well. There is also secular time variability unrelated to the changing orientation. To explain the gap, on top of synchrotron self-absorption we need free-free absorption by either a well bounded disk around the binary system with 25–30 AU diameter, or an ionization front. The variable absorbing environment could be explained by a variable equatorial outflow from the accreting environment. Existence of both slow outflow (Chakrabarti and Matsuda, 1992) and fast wind (King et al., 2000) have been predicted in SS433.

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The unusually flat spectra of radio-jet X-ray binaries (RJXRB) up to the mm regime have been interpreted by conical jet models (e.g. Fender et al., 2000). The first Galactic radio-jet source, discovered to have a flat-spectrum compact jet region that can be described with conical jet models, was SS433 (Hjellming and Johnston, 1988; Vermeulen et al., 1993; Paragi et al., 1999). Recently Cyg X–1 (Stirling et al., 1998), GRS 1915+105 (Dhawan et al., 2000) and LS 5039 (Paredes et al., 2000) were shown to have a faint compact jet region. However, a frequency-dependent core-shift (an indicator of self-absorbed compact jets) has not yet been observed in any of these sources.

2. The Equatorial Emission Region in SS433

An emission region spanning hundreds of AU, perpendicular to the radio beams, was discovered in SS433 (Paragi et al., 1999). The presence of this Equatorial Emission Region is confirmed in our 1.6 GHz global VLBI experiment, but also in some 5 GHz VLBA observations in 1998. Its structure is variable with timescales much shorter than a year, but considerably longer than a day. The brightness temperature is too high for thermal emission, which is probably due to optically thin synchrotron radiation originating in shocks in the ISM around the central engine. It was proposed by S. Fabrika (priv. comm.) that shocks develop due to the interaction of the slow outflow in the plane of the accretion disk and the faster disk wind, as the disk slowly turns during the precessional cycle. As similar "equatorial" radio components seem to exist in Cyg X-1 (Stirling et al., 1998), and there is evidence from IR spectral lines for an enchanced equatorial outflow in Cyg X-3 as well (Fender et al., 1999), this phenomenon might be common in RJXRBs.

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The Galactic Microquasar W50/SS433 system

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Abstract. We review the X-ray and millimeter observations of the W50 lobes associated with the twin-jet source SS433. This study is aimed at shedding light on the energetics from SS433, understanding the asymmetries of the lobes, and testing for cosmic ray acceleration in a Galactic twin-jet source.

Keywords: interstellar medium (ISM), W50, SS433, supernova remnants

1. X-ray Observations of the W50 lobes

W50 is the large supernova remnant (SNR) associated with the binary source SS433, famous for its twin-precessing jets. For a review of SS433 see Kotani (1997) and references therein. *ROSAT* and *ASCA* observations of W50 are summarized in Safi-Harb & Ögelman (1997). The X-ray images show two knotty X-ray lobes filling the space between SS433 and the radio ears. The X-ray spectrum softens away from SS433. Both thermal and non-thermal models give adequate fits to the *ROSAT* plus *ASCA* spectra.

W50 was later observed with the Rossi X-ray Timing Explorer (RXTE) to pin down the nature of its X-ray spectrum (Safi-Harb and Petre, 1999). Fitting the PCA spectrum of the *eastern* lobe in the 10–20 keV range, a power law model gives a better fit than a thermal bremsstrahlung model (Figure 1, left). The parameters derived from fitting the *RXTE* data with a thermal model are inconsistent with those derived using the *ASCA* data (Figure 1, right). We conclude that the spectrum is non-thermal.

The *western* lobe was recently observed with *RXTE*. Our preliminary results indicate the presence of an Fe-K emission line, which is likely associated with the Galactic ridge. A power law model yields a photon index Γ=1.7–2.0, while a thermal bremsstrahlung model yields a very high temperature kT= 6.5–10.2 keV (90% confidence level).

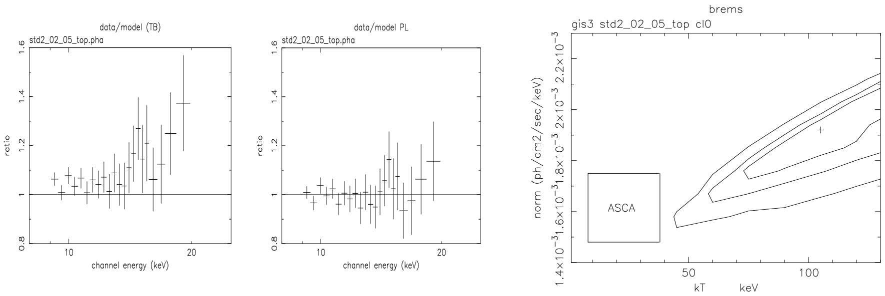

Figure 1. Left panel: The *RXTE* PCA data to fitted model. Right panel: Confidence contours for fitting *RXTE* with a thermal model.

2. Millimeter Observations

W50 was observed with *NOBEYAMA*, *SEST*, & *MOPRA*. No emission was found from the eastern lobe. In the western lobe, a 50 km/s CO emission line was found along the jet axis and correlated with the X-ray spots detected with *ROSAT* (Durouchoux et al., 1998). The implied distance is 3.24±0.46 kpc, in agreement with Dubner et al. (1998).

3. Summary and Conclusions

The non-thermal X-ray emission from the eastern lobe is suggestive of synchrotron emission from the high-energy electrons accelerated at the jet-SNR shell interaction site, and hints that W50 could be an important site for cosmic ray acceleration. Millimeter observations of the western lobe show shock-excited regions arising from the western jet interacting with a molecular cloud. The total radiated luminosity from W50 is a very small fraction of the kinetic power of the SS433 jets. Most of the power goes into bloating W50 in the east-west direction and energizing the surrounding medium.

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Monitoring and modeling radio flares from microquasars

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Abstract. We present results of long-term daily monitoring of a sample of Galactic radio-emitting X-ray binaries showing relativistic jets (RJXRB): SS433, Cyg X-3, and GRS 1915+105, with the RATAN-600 radio telescope in the 0.6–22 GHz range.

We carried out the modeling calculations to understand the temporal (1–100 days) and spectral (1–22 GHz) dependence. We tested the finite jet segment models and we found that the geometry of the conical hollow jets is responsible for either a power law or an exponential decay of the flares.

SS433 was monitored for 100 days in 1997 and 120 days in 1999. From the quiescent radio light curves, we obtained clear evidence of a 6.04-day 10–15% modulation.

Three powerful flares (up to 13 Jy) from Cyg X-3 were detected in April 2000.

Keywords: microquasar, radio emission, synchrotron radiation

Results of the multi-frequency daily monitoring

Many (or all!) of the radio sources related with X-ray binaries have been resolved into relativistic jets, often with detectable proper motion of the radio-emitting blobs. We present results of long-term daily monitoring of a sample of these RJXRBs with the RATAN-600 radio telescope at 0.96, 2.3, 3.9, 7.7, 11.2 and 21.7 GHz. Many strong optically thin and thick flares were detected during the monitoring period (see Bursov and Trushkin, 1996; Trushkin, 1998). The basic model of the flares is the synchrotron emission evolution of two relativistic jets with conical geometry and an adiabatic expansion of the blobs, which are composed of relativistic electrons embedded in magnetic fields, moving away from the central source (Shklovskii, 1960; van der Laan, 1966; Hjellming and Johnston, 1988; Marti et al., 1992). The flare decay law is determined by the geometry of the conical hollow jets. The jet velocity, thermal and relativistic electron densities, and magnetic field intensity within the blobs can be derived from the fits.

Our monitoring of radio variability of RJXRB shows that the decay of a flare follows a power law, $S_\nu = S_0 t^{-2p}$, as predicted by the Shklovskii and van der Laan models, or an exponential law $S_\nu = S_0 e^{-t/\tau}$ (Fig.1), which is due to the initial exponential increase of the jet cone radius. Often $\tau \sim \nu^\beta$, where β ranged from -0.8 to -0.4; these flares decay faster at higher frequencies (see current light curves and the spectra animation at `http://cats.sao.ru/~satr/XB/`).

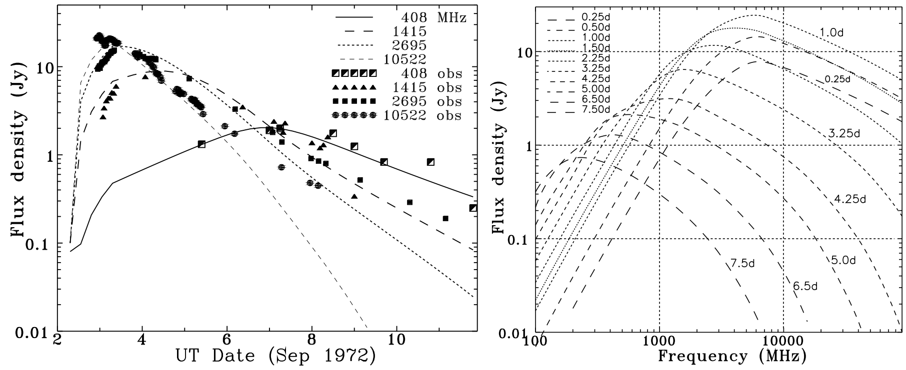

Figure 1. The model light curves at select frequencies (left) with the real data and the spectra of the famous Cyg X-3 flare at 2–11 September 1972 (right). The model parameters are from Marti et al. (1992)

We computed the power spectra of the daily light curves of SS433 in the 2.3–22 GHz range during the long quiescent periods May–July 1997 and May–August 1999. Both spectra show a mean harmonic at 0.165 ± 0.02 day^{-1}, which corresponds to a period of 6.04 ± 0.06 days.

We propose that Doppler boosting of the jet radiation could explain such modulation. The 5-elements kinematical model of the jets and ephemerides proposed by Vermeulen (1989) for the nodding motion of the jets and common formulas for boosting produce a modulation similar to the observed one. Thus we detect a 6-day modulation at the 10–15% level in the quiescent flux density, which is $S_\nu[\mathrm{Jy}] = 1.2\ \nu_{\mathrm{GHz}}^{-0.6}$.

Three powerful flaring events (up to 13 Jy) from Cyg X-3 were detected in April 2000. The daily spectra clearly show two components: i) a quasi-stable steep spectrum and ii) a very unstable flat spectrum.

In the wide range 0.6–22 GHz the optically thin spectrum of the detected strong flare of GRS 1915+10 (5 August, MJD 51751.85) is well fitted by the power law: $\mathrm{S}_\nu[\mathrm{Jy}] = 0.690\,\nu_{\mathrm{GHz}}^{-0.43}$.

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Elongated SNRs: Possible New Jet Sources

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Abstract. We summarise the properties of selected supernova remnants (SNRs) which have elongated envelopes that could house relativistic jets. We present MOPRA and SEST millimeter observations of these objects, showing correlation between known X-ray hot spots and molecular cloud density as signified by the detection of a CO(1-0) line flux.

1. Introduction

Some well known SNRs, e.g. Crab, SS433, are known to be associated with relativistic jets and are thus natural laboratories for studying the jet interaction with the surrounding material (e.g. Gaensler 1998, ApJ 493, 781). While examining SNR catalogues, we have found many more sources with elongated shapes which could be interpreted in terms of jet emission. Some of our observations are summarised below.

2. Observations of sources and results

SS433: The X-ray binary SS433, responsible for two oppositely directed relativistic jets, is located near the centre of the SNR W50. The jets are aligned with the radio wings of W50. We have observed a large molecular cloud in the direction of SS433/W50, and show that the CO(1-0) 50 km/s line flux is strongly correlated with the system's X-ray hot spots as detected by ROSAT and ASCA.

G309.2-00.6: G309.2-00.6 is a SNR analogous to SS433, with an appearance indicating opposite jets or outflows from a central source. A jet like feature, and breaks in the SNR shell can both be seen along the proposed axis of the outflow. We detected a molecular cloud (-43 km/s) in the direction of G309.2-00.6. The CO(1-0) line flux showed a correlation with the radio map of the source. Moreover, there was a correlation between the maxima of the mm line flux and the ASCA X-ray intensity for this source, again indicating an interaction of the jet with the ambient medium.

G41.1-0.3: The 3C397 complex consists of two radio sources, the East source which is a SNR (G41.1-0.3), and the West source, which is an HII region. G41.1-0.3 has an elongated shape in the radio, with brighter regions to the east and west. We observed a strong correlation between the CO(1-0) flux and the X-ray hot spot. The evidence for the interaction of a jet with the surrounding medium was strengthened by the detection of a CO(2-1) line flux which traces out the jet axis towards the west.

G54.1+0.3: G54.1+0.3 was identified as a Crab-line SNR in both the radio and X-ray bands. In high resolution VLA maps, G54.1+0.3 has a filled-centre brightness distribution which extends to the north-east and north, making this object a jet source candidate. The source has recently been shown to contain a 40" X-ray jet (Lu et al. 2000, these Proceedings). Our mm observations show that the CO(1-0) maximum strongly coincides with the X-ray maximum (Fig. 1).

Conclusions: Millimeter observations of galactic sources have shown that when a molecular cloud association is established with an elongated SNR, signatures of interactions with the ambient medium can be determined via CO(1-0) and CO(2-1) transitions. Such elongated SNRs may be further samples of galactic jet sources.

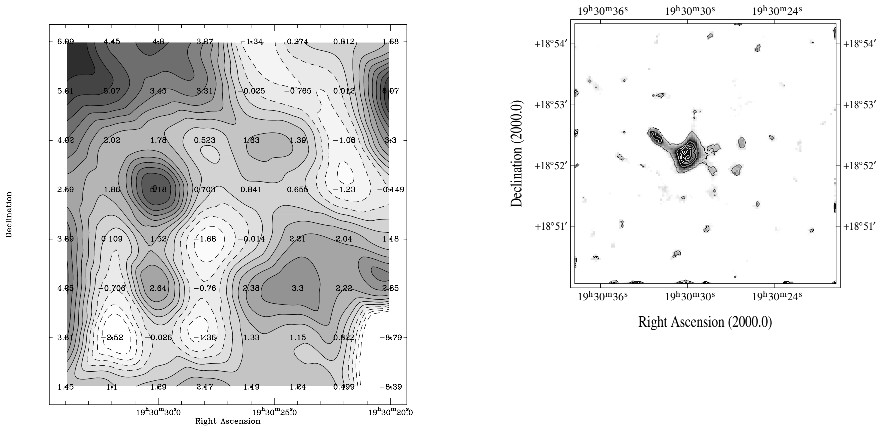

Figure 1. Millimeter (left) and X-ray (right) maps of G54.1+0.3

Discovery of an X-ray jet associated with supernova remnant G54.1+0.3 *

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Abstract. We present in this paper the discovery of an X-ray jet associated with the Crab-like supernova remnant G54.1+0.3. It points to the northeast with a length about 40″ from the center of the nebula and has a flux ∼1/6 of the whole remnant. The X-ray jet is consistent with the radio extension to the northeast, suggesting that it is connected with the pulsar embedded in the remnant.

1. Introduction

The radio source G54.1+0.3 was identified as a Crab-like SNR with radio extensions to the northeast and north, which are reminiscent of radio jets (Fig. 1, left panel) (Reich et al. 1985, Velusamy & Becker 1988). X-rays from G54.1+0.3 were firstly detected by the *Einstein* IPC but no extent to the X-ray emission was found (Seward 1989). We present here its X-ray image and spectrum from *ROSAT* PSPC and *ASCA* GIS and SIS data.

We use the *ROSAT* PSPC data to derive the X-ray image, while the *ASCA* SIS and GIS data are used in the spectral and temporal analyses, respectively. In order to improve the spatial resolution, we have deconvolved the X-ray image obtained by the *ROSAT* PSPC with the Lucy formula (Lucy 1974). In the iteration process the mean background is used as the lower limit constraint, in order to improve the quality of the deconvolved image, as proposed by Li & Wu (1994).

2. Results and discussion

The deconvolved X-ray image (0.1-2.4 keV) is shown in Fig. 1 (right panel), in which a jet-like feature (hereafter JLF) pointing to the northeast appears, in addition to the central bright nebula (hereafter CBN)

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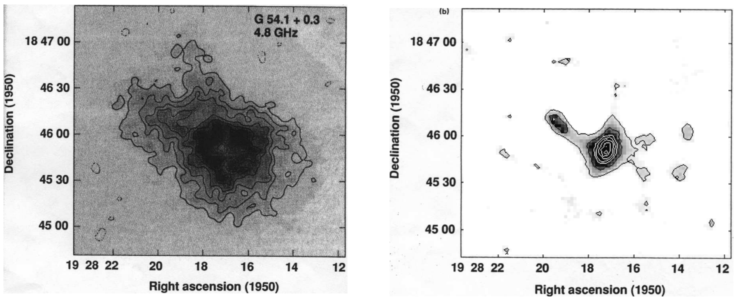

Figure 1. SNR G54.1+0.3. **(Left)**–The radio map obtained by VLA at 4.8 GHz (Velusamy & Becker 1988). **(Right)**–The 0.1-2.5 keV X-ray intensity map obtained by *ROSAT* PSPC and image deconvolution. The contour intervals are linear with a step size of 4×10^{-5} cnt s^{-1} per $2'' \times 2''$ pixel. The lowest contour corresponds to 2×10^{-5} cnt s^{-1} per pixel..

coinciding with the brightest radio region. The angular distance from the head of the JLF to the center of the CBN is about $40''$. The total photon flux of the CBN is about 2.07×10^{-2} counts s^{-1}, and that of the JLF is 3.9×10^{-3} counts s^{-1}.

We find that the power law spectral model gives the best fit of the data obtained by *ASCA* SIS. The derived parameters are: photon index α -$1.9^{+0.2}_{-0.2}$, column density N_H $17.9^{+2.8}_{-2.5}\times10^{21}$ cm^{-2}, 0.7-10.0 keV energy flux 1.138×10^{-11} erg cm^{-2} s^{-1}, reduced χ^2 0.7. The N_H value indicates a distance comparable with the radius of the galaxy, 10 kpc. The X-ray luminosity of G54.1+0.3 is $1.4\times10^{35}d_{10}^2$ erg s^{-1}, where d_{10} is the distance to G54.1+0.3 in unit of 10 kpc.

We examined the *ASCA* GIS data for temporal variability and have not detected any pulsation with significance of more than 3σ between 0.01 and 2.0 seconds. The upper limit of the pulsed fraction is 31% with the confidence of 90%.

Figure 1 shows nice coincidence of the X-ray JLF and radio extensions. It suggests that (1) the JLF is indeed an X-ray jet produced by the nonthermal electrons and that (2) these electrons are probably connected with the putative pulsar.

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