PROCEEDINGS OF SCIENCE

Predicting Radio Activity in X-ray Binaries with Optical/Infrared Monitoring

David M. Russell[*]
School of Physics and Astronomy, University of Southampton, Highfield, Southampton, England
E-mail: `davidr@science.uva.nl`

Rob P. Fender
School of Physics and Astronomy, University of Southampton, Highfield, Southampton, England
E-mail: `rpf@phys.soton.ac.uk`

X-ray binaries undergo outbursts due to increased mass accretion rate in the disc towards the compact object, a black hole or neutron star. Recently, a picture has developed where the behaviour between the radio, optical/infrared and X-ray luminosities during these outbursts are correlated. Here, I review this picture and show how simple optical/infrared monitoring can predict radio flux densities. Using these predictions it will be possible to prepare radio telescopes accordingly, eventually improving radio sampling of X-ray transients. In particular, it is possible to infer when the bright, optically thin jet flares are likely to occur in black hole transients. We find that the hard-to-soft X-ray state changes, which also can be identified by optical/infrared colour changes, lead the bright optically thin radio outbursts by ~ 10 days.

Bursts, Pulses and Flickering: wide-field monitoring of the dynamic radio sky
12-15 June 2007
Kerastari, Tripolis, Greece

PoS(Dynamic2007)012

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[*] Speaker.

1. Introduction

In low-mass X-ray binaries (LMXBs; in which a black hole or a neutron star accretes matter from a companion star via Roche lobe overflow), an increase in mass accretion rate causes an outburst. Outbursts are detected by changes in luminosity by up to eight orders of magnitude at X-ray energies, on timescales of days to years. These transients have been studied extensively at all wavelengths from γ-rays to radio, but the radio is not as well sampled as other regimes because it is generally harder for radio telescopes to achieve the sensitivity required in a reasonable amount of integration time. Specifically, most LMXB outbursts can be detected with a high level of confidence by 1-m class optical telescopes and X-ray all-sky monitors in a few minutes. There are fewer radio telescopes readily available with sensitivities of this order; longer on-source integrations are typically required compared to facilities available in the near-infrared (NIR), optical, ultraviolet or X-ray. In addition, the radio counterpart is normally *switched on* for only part of the time during an outburst [1].

To improve this deficiency in radio sampling, it would be advantageous to be able to predict when the radio counterpart is switched on and how bright it is expected to be at a given time during an outburst. If this is achieved, radio facilities can be prepared accordingly, resulting in improved efficiency of their usage and improved radio sampling of LMXBs.

2. Correlations between wavebands

Radio emission from LMXBs is thought to be synchrotron in nature and unambiguously originates in collimated outflows/jets (see [2] for a review). The processes responsible for the emission at other wavelengths are rich and often confusingly complex. However, striking correlations exist between the luminosities of different wavebands (especially in the black hole systems). These correlations depend on the X-ray spectral state in addition to the luminosity. In black hole X-ray binaries (BHXBs), the X-ray spectrum and timing properties can almost always be described by one of only a few distinct states [1, 3]. The two main X-ray spectral states are the *hard* (or *low/hard*) state, which is characterised by a hard power-law spectrum and strong variability, and the *soft* (or *high/soft*; *thermal–dominant*) state, where a thermal spectrum dominates with a power-law contribution and weak variability. The hard state is always accompanied by radio emission from a powerful compact jet, and has been observed at both high and low luminosities, whereas the soft state has no observed radio emission and is found to exist only at high luminosities [3]. Observations which fit neither of these states are generally transitional states and have typically been called *intermediate* states when at lower luminosities and *very high* states when at high luminosities. The low luminosity *quiescent* state is likely to be an extension to the hard state [1, 4, 5, 6] but currently this is not universally accepted.

A well-established relationship exists between X-ray luminosity and radio luminosity in BHXBs in the hard state; $L_{\rm radio} \propto L_{\rm X}^{0.7}$ [6, 7]. In the soft state, the radio is always suppressed or quenched, indicating the jet may be *switched off*. The transition from hard state to soft state appears to occur at higher luminosities than the transition back from the soft state to the hard state [1, 8].

The radio emission during the hard state originates in optically thick synchrotron emission from the jets, and takes the form of a flat or slightly inverted power-law ($\alpha \geq 0$, where $F_\nu \propto \nu^\alpha$)

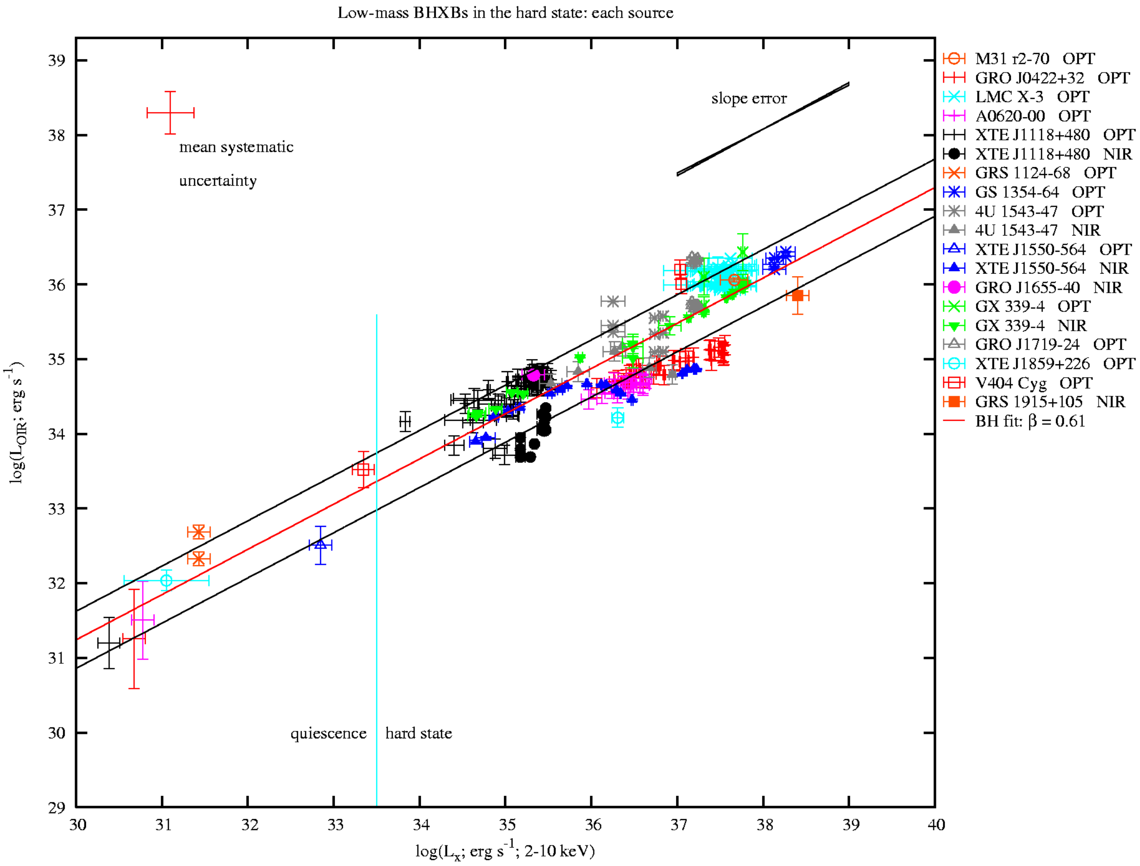

Figure 1: Quasi-simultaneous OIR and X-ray 2–10 keV luminosities of 16 BHXBs in the hard state [21, 22]. The fit to the data is $L_{\rm OIR} \propto L_{\rm X}^{0.6}$.

spectrum [9]. Evidence has been mounting that this flat spectrum may extend to the optical/NIR (OIR) regime or beyond from spectral [9, 10, 11] and timing [12, 13] studies. The optically thick synchrotron jet spectrum is predicted to break to an optically thin spectrum ($\alpha \sim -0.6$) at a ‘turnover’ at higher frequencies than the radio [14]. The position of this turnover is essential in estimating the power in the jets, as the radiative power is dominated by the higher energy photons. The electrons which produce these high energy photons dominate the internal energy (and hence total power) of the jet. The turnover is predicted to lie in the infrared according to some models [11] and this is now supported by a number of observations [15, 16, 17, 18, 19]. In addition, a drop and then rise in the OIR flux (moreso in the NIR than the optical) in transition from and to the hard state respectively has been noted in some sources [16, 18, 20], similar to the soft state quenching of the radio jet.

In 2006, quasi-simultaneous OIR and X-ray data of 16 BHXBs were collected from the literature and a global correlation was found in the hard state: $L_{\rm OIR} \propto L_{\rm X}^{0.6}$ (Fig. 1) [21, 22]. Optical light from LMXBs in outburst is generally thought to be dominated by X-ray reprocessing in the accretion disc. It was shown [23] that this process should produce a relation between optical and X-ray luminosities of the form $L_{\rm optical} \propto L_{\rm X}^{0.5} a$ where a is the orbital separation of the system. However, if the $\sim$ flat ($\alpha \sim 0$) optically thick jet spectrum extends to the OIR and dominates this waveband

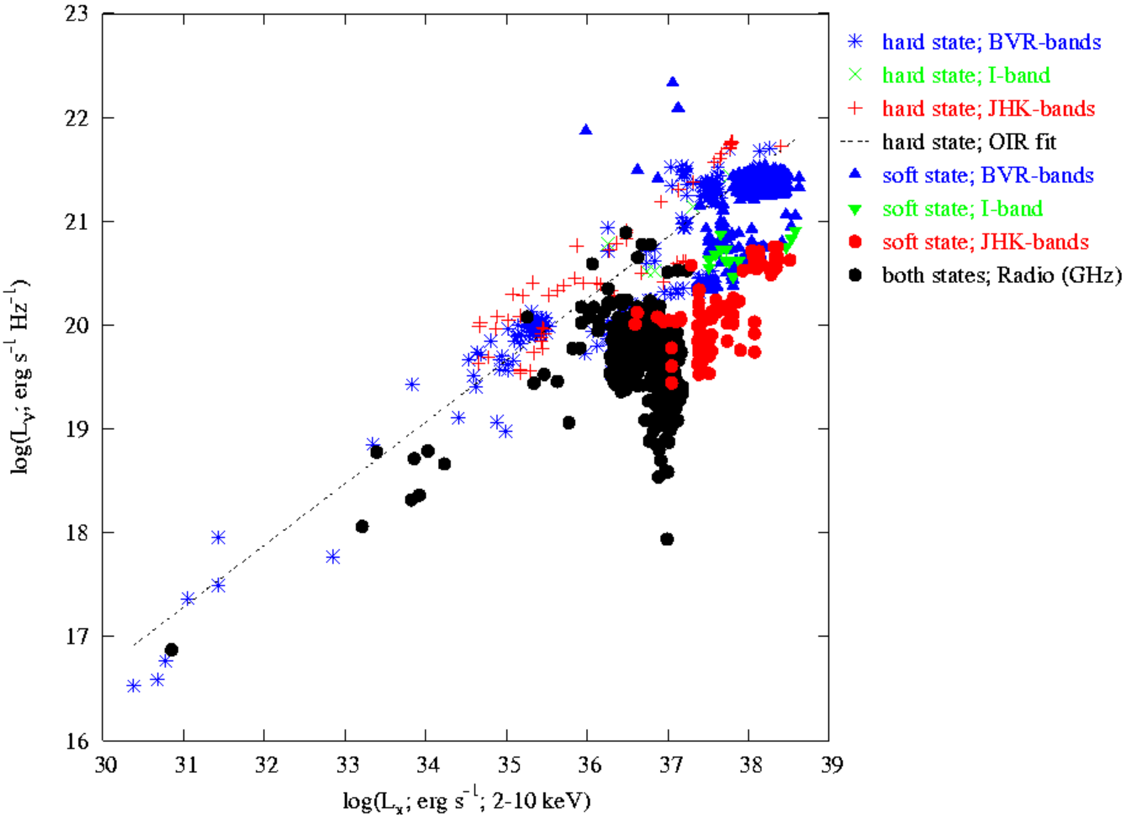

Figure 2: X-ray luminosity versus OIR and radio monochromatic luminosities (flux densities scaled with distance) for BHXBs [21]. The radio data are from [6] and [24].

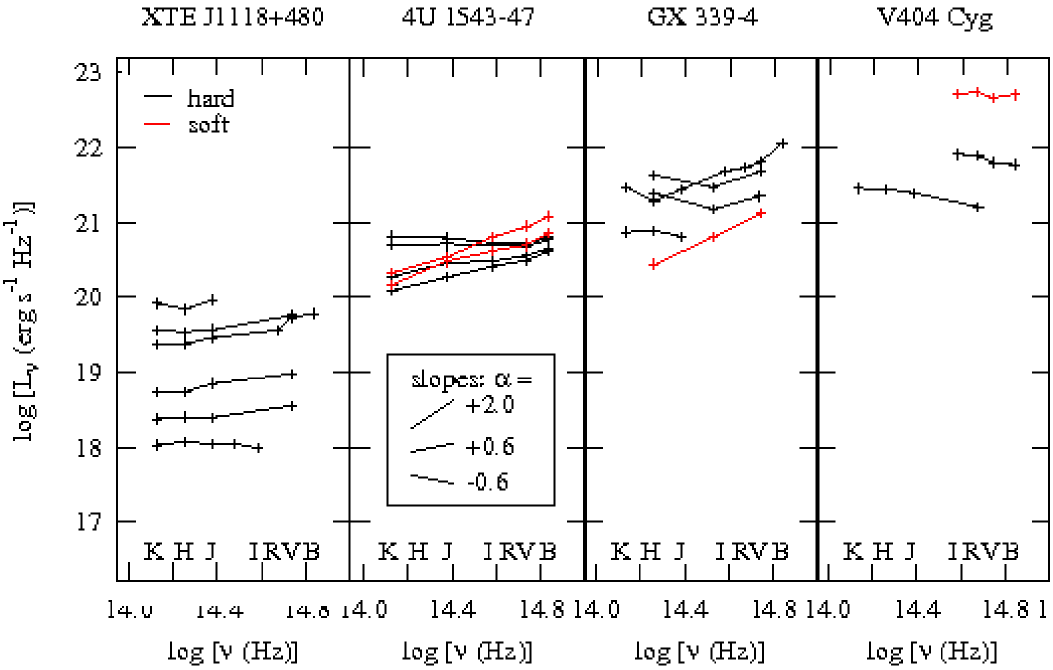

Figure 3: OIR spectral energy distributions (SEDs) of BHXBs in the hard (black) and soft (red) state [21].

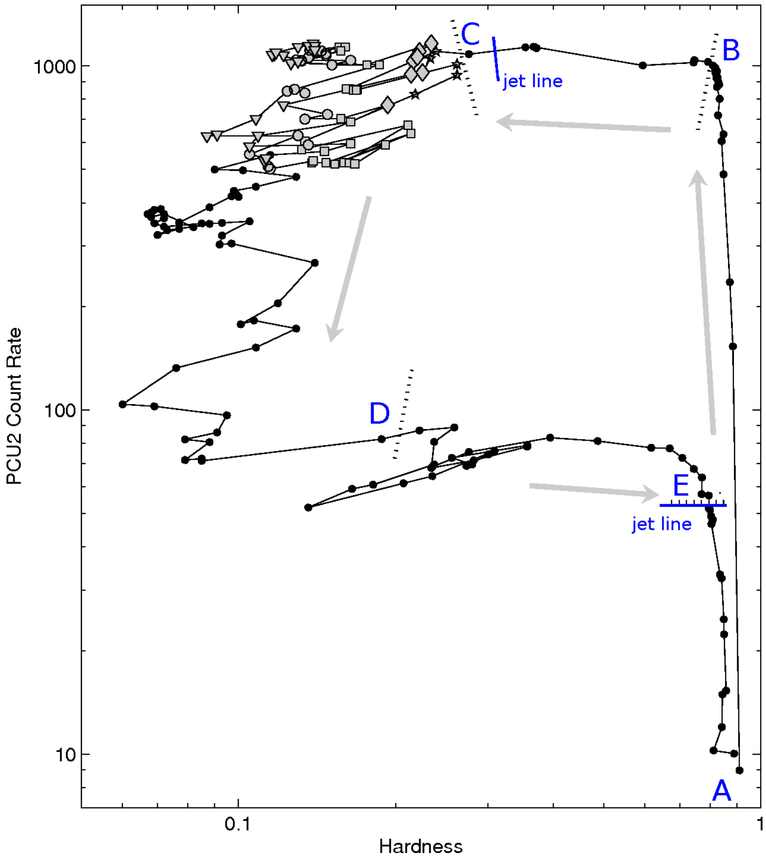

Figure 4: X-ray hardness–intensity diagram (HID) of GX 339–4 (adapted from [25]). The location of the jet line on the lower branch is highly speculative; the core jet may return at or before E.

we expect $L_{\rm OIR} \propto L_{\rm radio}$ and therefore $L_{\rm OIR} \propto L_{\rm X}^{0.7}$. In fact at a given X-ray luminosity the radio and OIR monochromatic luminosities are approximately equal, implying a flat radio-to-OIR spectrum at all luminosities in the hard state (Fig. 2), so the jet interpretation is valid in that respect. In addition, a clear suppression of all the NIR data (but not the optical) is seen in the soft state (Fig. 2). The level of quenching infers a jet contribution of $\sim$90% in the NIR during periods at high X-ray luminosity in the hard state.

This interpretation is supported by spectral energy distributions (SEDs; Fig. 3) of BHXBs. During the hard state (black data in the figure), two components of emission join in the OIR region; one with $\alpha < 0$ (which is interpreted as optically thin emission from the jet) and one with $\alpha > 0$ (presumably the disc component). In the soft state (red data) the $\alpha < 0$ component disappears below the level of the $\alpha > 0$ component. It seems that in the hard state, the optical emission is mainly dominated by the accretion disc (reprocessed X-rays) and the NIR is mainly dominated by the jet, which is quenched in the soft state. Both components scale with X-ray luminosity to about the same power in the hard state, which produces the observed $L_{\rm OIR} \propto L_{\rm X}^{0.6}$ [21].

3. The story of an outburst

A general picture of the X-ray behaviour of transient BHXB outbursts has now emerged [1]

Table 1: The observed time between the hard–soft state transition and the bright optically thin radio flare.

Source	Year of outburst	Number of days from B to 'jet line'	References
XTE J1550–564	2000	10	[26]
GX 339–4	2002	11	[18, 27]
H1743–322	2003	7	[28]
GRO J1655–40	2005	12	[29, 30]
GX 339–4	2007	$\leq$10	[31, 32]

in which a typical outburst follows a specific path in an X-ray hardness–intensity diagram (HID; Fig. 4). The radio behaviour is dependent on the position in the diagram (see Fig. 7 in [1]). Since the OIR is correlated with X-ray and radio luminosity, all three wavebands can now be included in the picture. This allows predictions of the behaviour of one waveband from the behaviour of another. In this scenario, the radio luminosity during an outburst can be predicted from OIR or X-ray luminosities.

At the beginning stages of a BHXB outburst the source is in the hard state, and luminosity rises as $L_{\rm OIR} \propto L_{\rm radio} \propto L_{\rm X}^{0.6-0.7}$ (stage A to B in Fig. 4). Some sources do not make a state transition [33] and decline in luminosity back into quiescence. If a source instead makes a transition, the X-ray spectrum softens at B and the NIR (and optical to some extent) starts to drop but the radio persists until the 'jet line'. Here, a bright radio flare is seen and the jet is thought to be then quenched at C. The time taken for a source to travel from position B to the jet line is remarkably similar between sources; $\sim$ 7–12 days (Table 1). Therefore, if a drop in the NIR luminosity, or a softening in the X-ray spectrum is detected, radio telescopes can be prepared for observing the fast, bright radio flare $\sim$ 7–12 days later. If regular OIR monitoring is taking place and the X-ray counterpart is being monitored by an all-sky monitor only (i.e. not pointed observations), it will be easier to identify this colour change from the OIR data than from the X-ray.

From C to D no radio emission from the steady jet (core) is detected and the X-ray spectrum is soft. Radio emission is sometimes detected in the soft state from a fading optically thin source which can be spatially resolved (e.g. jet shock material); this is consistent with a component physically separated from the core. The source transits back into the hard state at E and the steady jet returns either before [34] or at [17] E. The NIR appears to take a number of days to rise once back in the hard state (Fig. 5; upper panels); this could be due to the spectrum of the jet becoming optically thick at higher frequencies with time, as the jet is formed and builds up (the jet may start off optically thin at radio frequencies). It has been shown [35, 22] that in at least one source the NIR is more luminous at a given X-ray luminosity on the decline of an outburst compared with on the rise, while maintaining approximately the same hard state correlation slope (Fig. 5; lower panel). This effect may be caused by a shift in the radiative efficiency of the inflowing or outflowing matter, or variations in the disc viscosity or the spectrum/power of the jet. The radio, OIR and X-ray then all drop to quiescence following the correlations unless a secondary outburst is initiated in the mean time again by increased mass accretion.

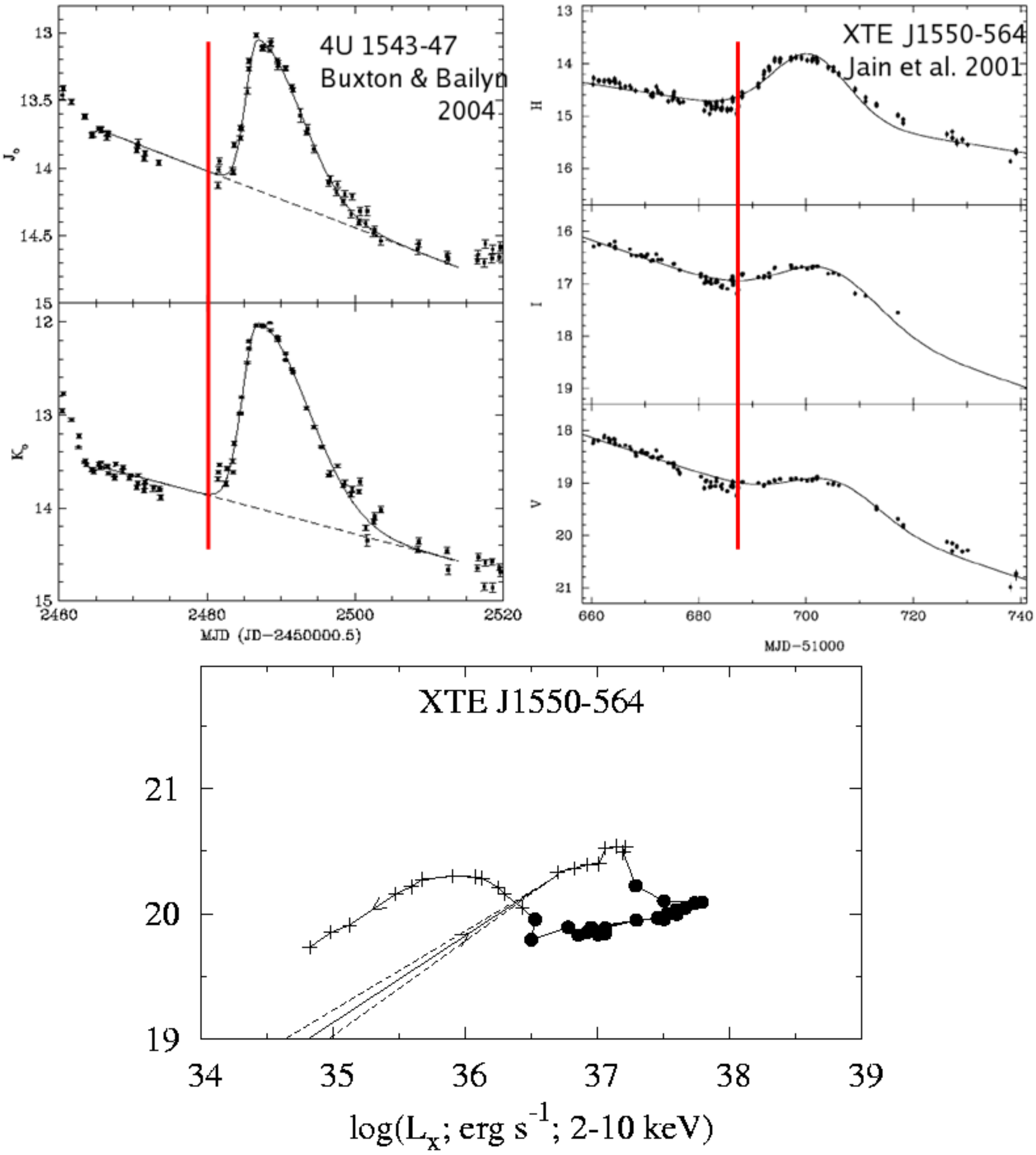

Figure 5: Upper panels: the OIR rise in flux after the return to the hard state (red lines) in two sources [16, 20]. It takes several days for the NIR counterpart (and the optical to a lesser extent) to rise and join the hard state OIR–radio–X-ray correlations. Lower panel: NIR versus X-ray luminosity of XTE J1550–564 during the 2000 outburst [35, 22]. Crosses are hard state data and filled circles are soft state data when the jet is quenched.

4. Summary

It is possible to predict the radio behaviour of a black hole X-ray binary in outburst from optical/infrared monitoring. It is hoped that these predictions will result in increased radio sampling during outbursts via prior knowledge of their approximate radio fluxes, allowing us to understand more fully the behaviour of the jets. There are currently a few telescopes dedicated to OIR monitoring of X-ray transients, such as SMARTS and the Faulkes Telescopes North and South [32, 36, 37, 38].

In a BHXB outburst, the radio flux density is roughly equal to the OIR flux density in the hard state, which are both proportional to $L_{\rm X}^{0.6-0.7}$. If/when the NIR (and optical to a lesser extent) starts to drop (at state transition), a bright radio flare is expected ∼10 days later. The radio jet is re-activated around the time of the return to the hard state, and the NIR rises just after this transition. Finally, the radio, OIR and X-ray fluxes then decay to quiescence. We suggest this scenario is universal for BHXB transients, but multi-wavelength campaigns are required to confirm this.

In addition, these techniques may also be useful for neutron star X-ray binaries, for which little radio observations have been made and the jet spectral slope is relatively unconstrained [39]. As a final thought, with many new radio telescopes arriving in the future including all-sky monitors, there is a danger that the X-ray behaviour of X-ray binaries will need to be predicted from the well-sampled radio!

References

[1] Fender, R. P., Belloni, T. M., Gallo, E. 2004, MNRAS, 355, 1105

[2] Fender R. P., 2006, in Compact Stellar X-Ray Sources, eds. Lewin W. H. G., van der Klis M., Cambridge University Press, p. 381

[3] Homan J., Belloni T., 2005, Ap&SS, 300, 107

[4] Narayan R., 1996, ApJ, 462, 136

[5] Tomsick A., Kalemci E., Kaaret P., 2004, ApJ, 601, 439

[6] Gallo E., et al., 2006, MNRAS, 370, 1351

[7] Corbel S., Nowak M. A., Fender R. P., Tzioumis A. K., Markoff, S. 2003, A&A, 400, 1007

[8] Maccarone T. J., Coppi P. S., 2003, MNRAS, 338, 189

[9] Fender R. P., 2001, MNRAS, 322, 31

[10] Han, X., Hjellming, R. M. 1992, ApJ, 400, 304

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

[12] Kanbach G., Straubmeier C., Spruit H. C., Belloni T., 2001, Nat, 414, 180

[13] Uemura M., et al., 2004, PASJ, 56, 61

[14] Blandford R. D., Konigl A., 1979, ApJ, 232, 34

[15] Corbel S., Fender R. P., 2002, ApJ, 573, L35

[16] Buxton, M. M., Bailyn, C. D. 2004, ApJ, 615, 880

[17] Kalemci E., et al., 2005, ApJ, 622, 508

[18] Homan J., Buxton M., Markoff S., Bailyn C. D., Nespoli E., Belloni T., 2005, ApJ, 624, 295

[19] Hynes R. I., et al., 2006, ApJ, 651, 401

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

[21] Russell D. M., Fender R. P., Hynes R. I., Brocksopp C., Homan J., Jonker P. G., Buxton M. M., 2006, MNRAS, 371, 1334

[22] Russell D. M., 2008, Ph.D. Thesis, University of Southampton (arXiv:0802.0816)

[23] van Paradijs J., McClintock J. E., 1994, A&A, 290, 133

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

[25] Belloni T., Homan J., Casella P., van der Klis M., Nespoli E., Lewin W. H. G., Miller J. M., Méndez M., 2005, A&A, 440, 207

[26] Rodriguez J., Corbel S., Tomsick J. A., 2003, ApJ, 595, 1032

[27] Gallo E., Corbel S., Fender R. P., Maccarone T. J., Tzioumis A. K., 2004, MNRAS, 347, L52

[28] McClintock J. E., Remillard R. A., Rupen M. P., Torres M. A. P., Steeghs D., Levine A. M., Orosz J. A., 2007, ApJ, submitted (arXiv:0705.1034)

[29] Homan J., 2005, ATel, 440

[30] Rupen M. P., Dhawan V., Mioduszewski A. J., 2005, ATel, 443

[31] Corbel S., Tzioumis T., Brocksopp C., Fender R., 2007, ATel, 1007

[32] Buxton M., Bailyn C., 2007, ATel, 1027

[33] Brocksopp, C., Bandyopadhyay, R. M., Fender, R. P. 2004, NewA, 9, 249

[34] Fender R. P., et al., 2007, in preparation

[35] Russell D. M., Maccarone T. J., Körding E. G., Homan J., 2007, MNRAS, 379, 1401

[36] Lewis F., Russell D. M., Fender R. P., Roche P., 2006, Proceedings of the VI Microquasar Workshop: Microquasars and Beyond. September 18-22, 2006, Como, Italy., p.82

[37] Maitra D., et al., 2007a, these proceedings

[38] Maitra D., Russell D. M., Lewis F., Bailyn C., Fender R. P., Roche P., 2007b, ATel, 1218

[39] Migliari S., Fender R. P., 2006, MNRAS, 366, 79