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# An anticorrelation between X-ray luminosity and H $\alpha$ equivalent width in X-ray binaries

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## ABSTRACT

We report an anticorrelation between continuum luminosity and the equivalent width (EW) of the H $\alpha$  emission line in X-ray binary systems. The effect is evident both in a universal monotonic increase in H $\alpha$  EW with time following outbursts, as systems fade, and in a comparison between measured EWs and contemporaneous X-ray measurements. The effect is most clear for black hole binaries in the low/hard X-ray state, which is prevalent at X-ray luminosities below  $\sim 1$  per cent of the Eddington luminosity. We do not find strong evidence for significant changes in line profiles across accretion state changes, but this is hampered by a lack of good data at such times. The observed anticorrelation, highly significant for black hole binaries, is only marginally so for neutron star systems, for which there are far less data. Comparison with previously established correlations between optical and X-ray luminosity suggests that the line luminosity is falling as the X-ray and optical luminosities drop, but not as fast, approximately, as  $L_{\text{H}\alpha} \propto L_{\text{X}}^{\sim 0.4} \propto L_{\text{opt}}^{\sim 0.7}$ . We briefly discuss possible origins for such an effect, including the optical depth, form of the irradiating spectrum and geometry of the accretion flow. Further refinement of the relation in the future may allow measurements of H $\alpha$  EW to be used to estimate the luminosity of, and hence the distance to, X-ray binary systems. Beyond this, further progress will require a better sample of spectrophotometric data.

**Key words:** accretion, accretion discs – X-rays: binaries.

## 1 INTRODUCTION

The process of accretion is the power source driving the luminosities for a wide range of objects, including protostars, binary systems containing accreting white dwarfs, neutron stars (NSs) or black holes (BHs), gamma-ray bursts and supermassive BHs in active galactic nuclei (AGN). A comprehensive review of this process is provided by Frank, King & Raine (2002).

In most of these systems, most of the time, the accretion process proceeds via an accretion disc which transports angular momentum outwards and matter inwards. The temperature of this disc increases towards the centre, and is a function of accretion rate and central accretor mass. The disc may also produce (or even be partially replaced by) at various times a relatively cool disc wind, a very hot corona and a collimated relativistic outflow or ‘jet’. Finally, the ‘state’ of the accretion flow at the centre of the disc may vary dramatically indicating rapid variations between phases with differ-

ent geometries, temperatures and outflows. Reviews of observation of accretion on to white dwarfs, NSs and BHs in binary systems can be found in, for example, Warner (2003) and Charles & Coe (2006).

In X-ray binary systems containing an accreting NS or BH, the region of the accretion disc responsible for the optical continuum and emission lines lies at a large distance from the central accretor (several light seconds, or  $\geq 10^4$  gravitational radii – e.g. Hynes et al. 2006). Many such systems are transients, in that they display phases of very high luminosities lasting typically weeks to months, followed by long periods in quiescence (e.g. Chen, Shrader & Livio 1997). Such cycles are likely to have their origin in accretion disc instabilities associated with hydrogen ionization (Frank et al. 2002 and references therein).

It is widely accepted that the emission lines in such systems arise in the rotating accretion disc flow. The strongest evidence for this interpretation is in the form of twin-peaked line profiles (e.g. Horne & Marsh 1986; Charles & Coe 2006 and references therein). The dominant pumping mechanism for these lines is likely to be the irradiation by the central X-ray source at high luminosities, as is

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observed for the optical continuum (van Paradijs & McClintock 1994). At lower luminosities, viscous heating of the disc may contribute significantly.

However, the picture may not be so simple. Russell et al. (2006, and references therein) have demonstrated that in BH X-ray binaries (BHXBs) in ‘hard’ X-ray states synchrotron emission from the jet dominates the continuum in the near-infrared and can contribute significantly in the optical band. Wu et al. (2001, 2002) argue for three distinct origins for the emission line depending on the source luminosity and spectral states. In their model, in bright/soft X-ray states the line arises in the atmosphere of an optically thick disc, whereas in bright/hard X-ray states the  $H\alpha$  line arises in a dense outflow. In the faintest quiescent states, the whole accretion flow is optically thin.

In a related work, Eikenberry et al. (1998) found a near-linear correlation between  $\text{Br}\gamma$  (2.166  $\mu\text{m}$ ) integrated line flux and the adjacent continuum flux density in the BHXB GRS 1915+105, during phases when the continuum was likely to be synchrotron emission from the powerful jet in this source. This suggests radiative pumping of the lines by the ultraviolet (UV) emission from the jet. A comparison with phases of soft X-ray spectra with no jet emission in the same study was taken to indicate that the jet is a far better source of photoionizing photons than the inner accretion disc, presumably due to the fact that the UV-emitting region of the jet is raised above the disc and illuminates it very efficiently (this argument does not work if this region of the jet is moving relativistically away from the disc and therefore strongly Doppler deboosted). However, a strong change in  $H\alpha$  EW associated with X-ray state, and therefore jet production, is *not* observed in GX 339–4 (Wu et al. 2001; see also Fig. 1), possibly arguing against strong pumping of  $H\alpha$  by the jet.

In this paper, we have compiled measurements of the strength of  $H\alpha$ , the most prominent emission line in the optical spectra of X-ray binaries. Our goal was to see how the properties of the emission line varied, if at all, with accretion ‘state’ and luminosity of X-ray binary systems, and whether or not there was clear evidence for

phases where the lines were formed in an outflow rather than a disc. What we find is evidence for an anticorrelation between the equivalent width (EW, ratio of line to local continuum flux) and overall luminosity of such systems, in particular, when in the ‘hard’ X-ray state (at luminosities below about 1 per cent of the Eddington limit).

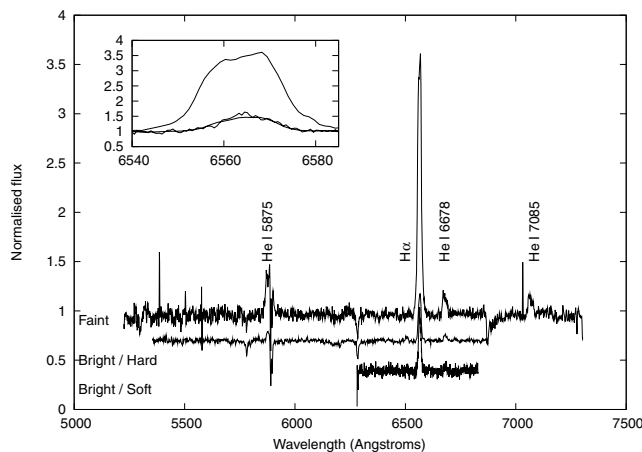
## 2 AN ANTICORRELATION BETWEEN $H\alpha$ EW AND LUMINOSITY IN BLACK HOLE X-RAY BINARIES

Two approaches, discussed below, are taken in order to investigate the relation between emission line strength and luminosity in BHXBs. In the first, we track the EW of  $H\alpha$  as a function of time following an X-ray outburst, in which case the general trend of the relation with luminosity is inferred (albeit quite confidently); in the second approach, we directly compare  $H\alpha$  EW with X-ray luminosity, a more direct approach but one which is limited by a lack of data at low luminosities.

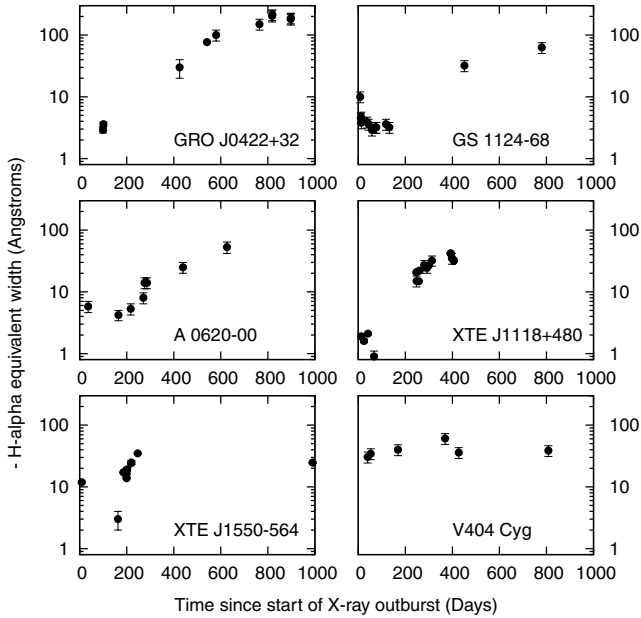
Before doing so, we present in Fig. 1 optical spectra in the  $H\alpha$  region for the BHXB GX 339–4 in three ‘states’: a very faint state (upper spectrum), a bright state with a hard X-ray spectrum (middle spectrum) and a bright state with a soft X-ray spectrum (lower spectrum). What is immediately clear is that in the faint state the  $H\alpha$  EW is much greater than it is in either of the higher luminosity states, and also that there does not appear to be much change in the line EW (or profile) between the two high-luminosity states. Indications of the optical magnitudes and EWs at the different epochs are given in the figure caption. See Soria, Wu & Johnston (1999) and Shahbaz, Fender & Charles (2001) for a detailed discussion of these spectra.

### 2.1 Trends of increasing $H\alpha$ EW during outburst decays

Most X-ray transients (with both BH and NS accretors) follow a monotonic decay (with some occasional rebrightenings) in X-ray luminosity after the first few weeks or months of outburst. Specifically, Chen et al. (1997) noted a mean exponential decay time-scale for X-ray transients of around 30 d in the initial decline from outburst. Such a decay rate indicates that within 2 yr a source should have returned to a ‘quiescent’ level, typically a factor of  $\sim 10^7$  fainter in  $L_X$  than at the peak of outburst. As a caveat, it should be noted that the observed decays are often far from simple exponentials. Nevertheless, a trend of increasing EW with time following outburst would therefore be a strong indicator that there is a luminosity–EW anti-correlation. This effect is investigated in Fig. 2, where the time evolution of  $H\alpha$  EW is plotted for the first 1000 d following outburst, for six BHXBs, which for most sources should include the return to quiescence. The dates and references for these outbursts are given in Table 1. These were the only six sources for which we could find good coverage of the  $H\alpha$  EW following the outburst. A clear trend of increasing EW with time is observed in the first four sources (GRO J0422+32, GS 1124–68, A0620–00 and XTE J1118+480), following an initial period of erratic variations or dips, which probably corresponds to points before the monotonic decay had begun. The fifth source, XTE J1550–564, shows a similar pattern of behaviour, but there are hints, at around 1000 d, of a subsequent decline in the EW. Inspection of the *RXTE* ASM monitoring at this time does not reveal any obvious subsequent outburst, but is not sensitive to activity below  $L_X \sim 10^{36}$  erg s $^{-1}$ . However, optical monitoring reported by Orosz et al. (2002) does in fact indicate that this final EW measurement was within 200 d of an additional optical outburst; therefore, its behaviour may not be discrepant. Note



**Figure 1.** Normalized optical spectra of GX 339–4 in low luminosity, bright/hard (–0.3 in normalization) and bright/soft (–0.6) states (Soria et al. 1999; Shahbaz et al. 2001). These spectra are almost certainly uncontaminated by a companion star. The strongest emission line is  $H\alpha$ , which clearly has a much greater EW in the faint state than in either of the brighter states. The inset shows the  $H\alpha$  profile for all three spectra plotted on the same scale. The bright/hard and bright/soft spectra, with  $H\alpha$  EW  $\sim 7$  Å, were simultaneous with photometric observations which recorded  $V \sim 16.5$ ; the faint-state observations, with  $H\alpha \sim 55$  Å were obtained when  $R = 20.1 \pm 0.1$ .



**Figure 2.** Variation of H $\alpha$  EW with time since X-ray discovery of six transient BH binaries. For the top four sources, GRO J0422+32, GS 1124–68, A0620–00 and XTE J1118+480, there is a clear increase in the EW with time. For XTE J1550–564, there is an initial increase but hints of a subsequent decline, and for V404 Cyg there is no clear trend. Assuming this is a representative sample, this strongly suggests an anticorrelation of EW with luminosity as the majority of BH transients fade following outbursts.

that for some of the other sources there is evidence in the literature for minor rebrightenings after 200 d which should not affect the broad conclusions here but may have some relevance for the poorer anticorrelation between X-ray luminosity and quasi-simultaneous

EW measurements in the next section. Finally in the sixth panel, V404 Cyg, which was in several ways an unusual transient (e.g. Kitamoto et al. 1989) and is far more luminous in ‘quiescence’ than most BHXBs, does not display any clear trend of increasing EW following its outburst.

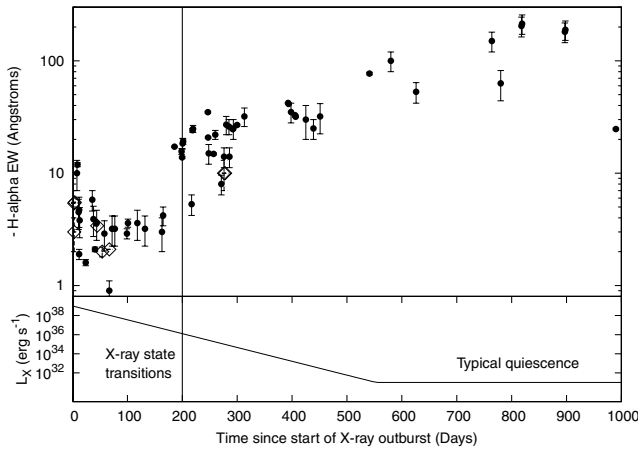
Therefore, it does seem that for the majority (five of six) of the sources, there is an increase in H $\alpha$  EW following outburst, which strongly suggests an anticorrelation between luminosity and H $\alpha$  EW in these systems. We have no reason to believe that our sample is strongly biased, but the sample of available EW data is clearly small and it is probably too early to quantify the diversity in these general EW trends.

In Fig. 3, we overplot the data for the first five sources from Fig. 2; i.e. all except V404 Cyg. The Spearman rank correlation coefficient for the increase in EW with time for the sample of all six sources is  $r_s = 0.82$ , a rank correlation at the  $6.8\sigma$  level. Removing V404 Cyg, the most discrepant source and arguably a ‘non-standard’ transient (i.e. the data set plotted in Fig. 3), increases these figures slightly to  $r_s = 0.89$ , corresponding to a rank correlation at the  $7.1\sigma$  level. Adding a small number of additional points for the sources GS 2000+25, XTE J1650–500, XTE J1859+226 and GRS 1009–45 increases the significance of the correlation to  $7.3\sigma$  (see Table 1 for references). Table 2 presents a compilation of the Spearman rank correlation coefficients and their significance for most of the samples discussed in this paper.

Fig. 3 does, however, also hint at a complication to the picture, namely that the correlation between elapsed time and H $\alpha$  EW is clearer after about 200 d, which is around the time that most sources are expected to have made a transition back to the hard X-ray spectral state, at a (2–10 keV) X-ray luminosity of a few times  $10^{37}$  erg s $^{-1}$  (Maccarone 2003; Homan & Belloni 2005). At this point, the steady, powerful jet associated with this state is expected to be reactivated after a period in the soft X-ray state in

**Table 1.** X-ray binaries used in this study, with relevant references.

Source BH binaries	References
GRO J0422+32	Callanan et al. (1995), Bonnet-Bidaud & Mouchet (1995), Garcia et al. (1996), Casares et al. (1995a), Harlaftis et al. (1999)
A 0620–00	Whelan et al. (1977), Murdin et al. (1980), Marsh et al. (1994)
XTE J1118+480	Torres et al. (2004), Zurita (private communication)
GS 1124–68	Orosz et al. (1994), della Valle, Masetti & Bianchini (1998), Casares et al. (1997), Sutaria et al. (2002), Ebisawa et al. (1994)
XTE J1550–564	Orosz et al. (2002), Sanchez-Fernandez et al. (1999), Casares, Dubus & Homer (1999), Buxton et al. (1999)
GRO J1655–40	Bianchini et al. (1997), Shahbaz et al. (2000), Soria, Wu & Hunstead (2000)
GX 339–4	Grindlay (1979), Soria et al. (1999), Shahbaz et al. (2001)
GS 2000+25	Charles et al. (1988), Shahbaz et al. (1996), Tsunemi et al. (1989), Casares et al. (1995a), Garcia et al. (2001)
XTE J1650–500	Augusteijn et al. (2001), Sanchez-Fernandez et al. (2002)
XTE J1859+226	Garnavich, Stanek & Berlind (1999), Wagner et al. (1999), Zurita et al. (2002)
GRS 1009–45	della Valle et al. (1997)
V404 Cyg	Casares et al. (1991, 1993), Hynes et al. (2004)
4U 1957+11	Shahbaz et al. (1996)
NS binaries	
Aql X-1	Charles et al. (1980), Shahbaz et al. (1996), Garcia et al. (1999), Shahbaz et al. (1998)
Cen X-4	van Paradijs et al. (1980) and 1987, Shahbaz et al. (1996), Campana et al. (2004)
Sco X-1	Shahbaz et al. (1996)
Cyg X-2	Shahbaz et al. (1996)
EXO 0748–676	Pearson et al. (2006)
IGR 00291+5934	Torres et al. (2004), Filippenko, Foley & Callanan (2004)
SAX J1808.4–3658	Campana et al. (2004), Campana & Stella (2004)
XTE J1814–338	Steehgs (2003), Papitto et al. (2007)
HETE J1900.1–2455	Elebert et al. (2008)
XTE J2123–058	Casares et al. (2002), Tomsick et al. (2004)



**Figure 3.** The data for the first five sources in Fig. 1 overplotted (filled circles), plus a small number of additional measurements (open diamonds; see the text for details). The similarity in the post-outburst time evolution of the H $\alpha$  EW is remarkable. In the lower panel is a crude approximation of the X-ray luminosity evolution of the source based upon the typical exponential decay time-scale for transients (Chen et al. 1997) and typical quiescent level (Remillard & McClintock 2006 and references therein). The vertical line at 200-d delay indicates the time after which all the sources should be in the hard spectral state; at earlier times, they could be in either soft or hard X-ray states (Maccarone 2003; Homan & Belloni 2005).

**Table 2.** Spearman rank correlation coefficients, and their significance in terms of standard deviations, for the relation of H $\alpha$  EW as a function of time since outburst (column 2) and X-ray luminosity (column 3). The ensemble values are presented in the last row. Gaps indicate sources for which there are too little data to make meaningful tests.

Source	EW versus time	EW versus $L_X$
GRO J0422+32	0.90 (2.7 $\sigma$ )	-0.90 (1.8 $\sigma$ )
GS 1124-68	-0.10 (0.3 $\sigma$ )	
A 0620-00	0.92 (2.4 $\sigma$ )	-0.56 (1.1 $\sigma$ )
XTE J1118+480	0.94 (4.2 $\sigma$ )	
XTE J1550-564	0.93 (2.9 $\sigma$ )	-0.91 (2.9 $\sigma$ )
V404 Cyg	0.54 (1.2 $\sigma$ )	
GX 339-4		-0.49 (1.1 $\sigma$ )
GRO J1655-40		0.41 (1.7 $\sigma$ )
BH ensemble	0.82 (6.8 $\sigma$ )	-0.48 (3.9 $\sigma$ )
NS ensemble	-	-0.68 (2.3 $\sigma$ )
BH+NS ensemble	-	-0.58 (5.1 $\sigma$ )

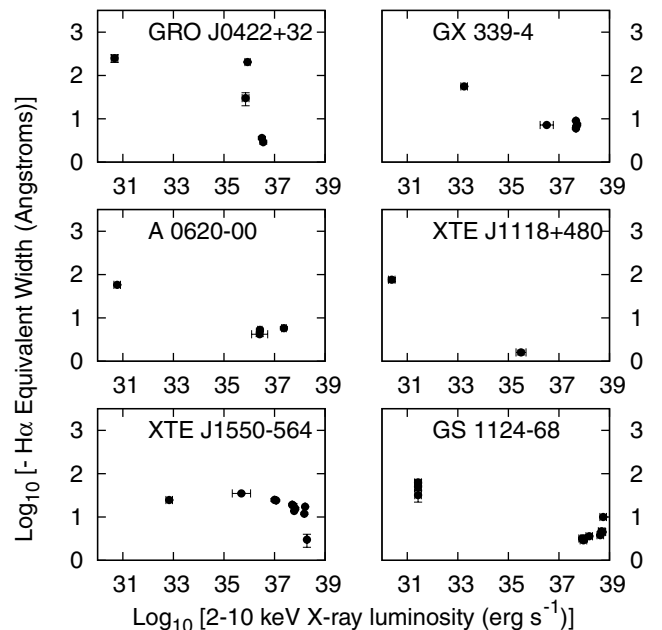
which it was suppressed (Fender, Belloni & Gallo 2004 and references therein). In order to investigate this effect, we separated the data from Fig. 3 at the point of 200 d (vertical line in Fig. 3). The data after this point, almost certainly exclusively in the hard X-ray state, still showed a significant correlation between elapsed time and the H $\alpha$  EW at the 5.1 $\sigma$  level ( $r_s = 0.80$ ). The sample of data prior to 200 d was not significantly correlated in any way with the elapsed time. The increase in overall significance for the entire sample can be attributed to the combination of the correlation in the hard X-ray state together with a generally lower EW in the ‘clump’ of data at shorter elapsed times, which will include a mix of luminous hard and soft X-ray states. Fig. 3 is a log-linear plot, therefore it is clear from the apparent linear relation that an exponen-

tial fit should be appropriate. A fit to the ensemble of data from 200 d onwards (excluding V404 Cyg), i.e. almost certainly in the hard state, indicates an e-folding time constant for the increase of H $\alpha$  EW of  $286 \pm 23$  d. If the 30-d e-folding decay time for the X-ray luminosity was an accurate estimate, then this would imply that  $EW \propto L_X^{-0.1}$  (approximately). We will test this in the next section. Note that the global correlation between X-ray and optical luminosities for BHXBs reported in Russell et al. (2006; see also van Paradijs & McClintock 1994) demonstrates that any anticorrelation found, or inferred, between EW and X-ray luminosity, is also one between EW and optical luminosity (hence the use of the generic term ‘luminosity’ in much of what follows).

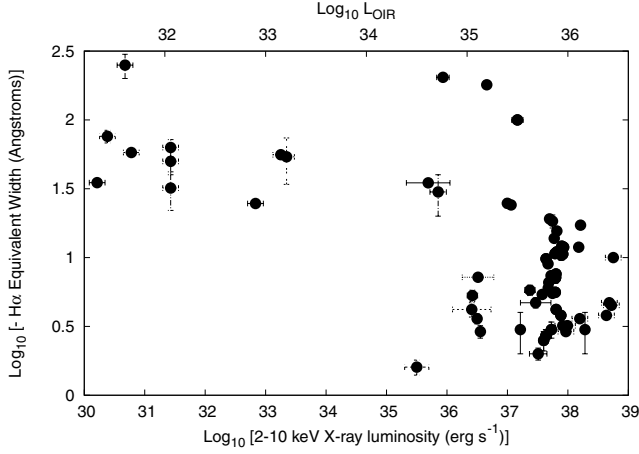
## 2.2 EW as a function of X-ray luminosity

The approach taken in Section 2.1, in plotting H $\alpha$  EW as a function of time for BHXBs, is a strong but indirect indication of an anticorrelation of the EW with luminosity. A more direct comparison of luminosity and EW would be desirable, to rule out some unexpected mechanism rather than luminosity changes dominating the observed effect. Unfortunately, the majority of the optical spectroscopic observations do not appear to be well flux-calibrated, so we cannot directly compare EW with optical continuum luminosity.

A second possibility is to compare with an X-ray measurement which has been made contemporaneously, which is what we attempt next. In order to be considered, the X-ray and optical spectroscopic measurements had to be made within 1 d of each other, except at quiescent levels at which we assumed that a more or less stable level had been reached (quiescent variability can reach factors of several, but this is not very significant for these logarithmic plots). In Fig. 4, we plot H $\alpha$  EW as a function of  $L_X$  for the sample of objects discussed previously (except for V404 Cyg for which we do not have contemporaneous X-ray measurements), plus the more unusual object GX 339-4. None of the individual sources shows



**Figure 4.** Variation of H $\alpha$  EW with estimated X-ray luminosity based on contemporaneous observations. The sources are the same as presented in Fig. 2, except that V404 Cyg has been replaced by GX 339-4. All sources show a general anticorrelation, although the patterns of behaviour are clearly not identical.



**Figure 5.**  $H\alpha$  EW as a function of contemporaneously measured X-ray luminosity (typically 2–10 keV). All the data from Fig. 4 are combined, as well as a small number of additional measurements (see the text for details). There is an overall rank anticorrelation, at a  $3.9\sigma$  confidence level. The upper  $x$ -axis indicates an estimate of the optical–infrared luminosity,  $L_{\text{OIR}}$ , calculated from the relation  $L_{\text{OIR}} = 10^{13.2} L_X^{0.60}$  for BH binaries presented in Russell et al. (2006).

a statistically significant rank (anti)correlation (see Table 2). In Fig. 5, we plot the ensemble of data points, plus a small amount of additional data from the sources V404 Cyg, GRO J1655–40, 4U 1957+11, GS 2000+25, XTE J1650–500 and XTE J1859+226 (see Table 1 for references).

A Spearman rank correlation test for the complete sample plotted in Fig. 5 results in a Spearman rank correlation coefficient of  $r_s = -0.48$  (a  $\sim 3.9\sigma$  result). This supports the conclusion of Section 2.1. A single power-law fit to the data presented in Fig. 5 gives

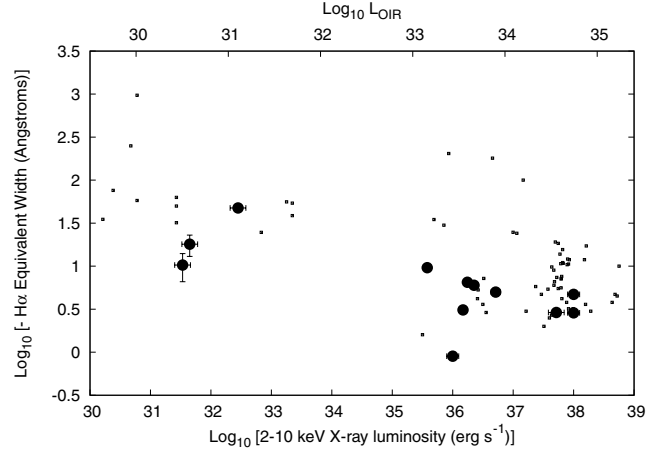
$$\text{EW} = (-24 \pm 18) \frac{L_X^{-0.18 \pm 0.06}}{10^{36}}.$$

This is close to, but steeper than, the  $\text{EW} \propto L_X^{-0.1}$  estimated in Section 2.1, and indicates a mean X-ray decay e-folding time less than the 30 d given in Chen et al. (1997). The apparent anticorrelation seems to be dominated by the difference between measurements at  $L_X \leq 10^{36} \text{ erg s}^{-1}$ , where all sources are in the hard X-ray spectral state, and those at higher luminosities, where transitions between different spectral states can occur (see e.g. Nowak 1995; Homan & Belloni 2005; Remillard & McClintock 2006 for a discussion of these states).

It is somewhat puzzling that the anticorrelation stands out much more clearly in the first analysis (Figs 2 and 3) than in the second (Figs 4 and 5), which implies that there may not be a simple one-to-one relation between X-ray luminosity and  $H\alpha$  EW. In this context, it is interesting to note that the low-frequency Quasi-Periodic Oscillation (QPOs) in some hard-state BH candidates show similar monotonic behaviour with time which is not so simple when compared to X-ray flux (e.g. XTE J1118+480 in Wood et al. 2001). In any case, the anticorrelation, whether simple or not, is clearly there.

### 2.2.1 Neutron star X-ray binaries

Far fewer results were available in the literature for NS systems; the details and references are provided in Table 1. In Fig. 6, we plot the NS data alongside the BH data presented in Fig. 5. What we



**Figure 6.** As Fig. 5, but for NS binaries (the BH sample from Fig. 5 is indicated as small dots). These points are consistent with NS X-ray binaries following a similar anticorrelation to BH binaries (with a hint of a lower normalization). As in Fig. 4, the upper  $x$ -axis indicates an estimate of  $L_{\text{OIR}}$  based upon the relation from Russell et al. (2006), which is  $L_{\text{OIR}} = 10^{9.7} L_X^{0.66}$ , slightly different to that for BHs (hence the slightly different range in  $L_{\text{OIR}}$ ).

see is approximately similar behaviour, in that there is a suggestion of a similar trend, with a similar (or slightly lower) normalization. In fact, a Spearman rank correlation test indicates that the sample of seven NS measurements are anticorrelated at the  $2.7\sigma$  level ( $r_s = -0.84$ ). So, the NS data are consistent with, but do not independently establish, the anticorrelation found for the BHXBs.

Adding the BHXB and NS samples results in a Spearman rank correlation coefficient of  $r_s = -0.58$ , corresponding to an anticorrelation at the  $5.1\sigma$  level.

In summary, although the individual, simultaneous  $L_X$  and EW measurements do not confirm the anticorrelation further, the effect is significant when considering the ensemble of all data points, more so when combining NS data with the BH sample.

### 2.3 Relation to optical continuum luminosity

The upper  $x$ -axes of Figs 5 and 6 also indicate a rough estimate of the optical–infrared luminosities,  $L_{\text{OIR}} = \nu L_\nu$ , based on the relations presented in Russell et al. (2006), and repeated in the figure captions (without statistical uncertainties). Note that the relations are slightly different for BHs and NSs ( $L_{\text{OIR}}$  is larger for BHs at any given X-ray luminosity). This allows us to get a better idea of how the EW varies as a function of the optical continuum.

Subject to caveats about the possibly complex nature of the relation to the lines, we can go further. By definition,

$$\text{EW} \propto \frac{L_{H\alpha}}{L_{\text{opt}}},$$

where  $L_{H\alpha}$  and  $L_{\text{opt}}$  are the line and continuum luminosities, respectively. From Russell et al. (2006),

$$L_{\text{OIR}} \propto L_X^c,$$

where the value of  $c$  is slightly different for BH and NS systems. We also fit a crude relation of the form

$$\text{EW} \propto L_X^d$$

above. If we can assume  $L_{\text{OIR}} \propto L_{\text{opt}}$  (i.e.  $L_{H\alpha} \ll L_{\text{opt}}$  which is justified for a maximum EW of  $\sim 100 \text{ \AA}$  and a filter width of

>1000 Å, and a large fraction of the data in Russell et al. (2006) being in the *R* band), we get

$$L_{H\alpha} \propto L_{OIR} L_X^d.$$

Substituting, we get

$$L_{H\alpha} \propto L_X^{c+d} \propto L_{opt}^{1+(d/c)}.$$

For the BHs,  $c \sim 0.6$  and  $d \sim -0.2$ , resulting in

$$L_{H\alpha} \propto L_X^{\sim 0.4} \propto L_{opt}^{\sim 0.7}.$$

Given the crudeness of the fit to the EW– $L_X$  relation, there seems little point in propagating uncertainties on these relations. While this analysis is crude, it does demonstrate that the  $H\alpha$  line luminosity must vary quite strongly with X-ray luminosity, but not quite as fast as the continuum.

### 3 THE ORIGIN OF THE LINES AND CONTINUUM IN BHXBS

A key diagnostic of the emission site of a spectral line is the line profile itself. A twin-peaked line profile is a strong indication that the line originates in a rotating flow, such as the atmospheres of geometrically thin accretion discs (e.g. Horne & Marsh 1986; note, however, that Murray & Chiang 1996, 1997, 1998 have shown that accretion discs with winds can produce single-peaked lines).

In Fig. 7, we indicate which lines, from the sample presented in Fig. 5, were reported as twin-peaked. We see that twin-peaked line profiles have been reported at nearly all luminosities, which strongly suggests that the line-emitting region is ubiquitously associated with the rotating accretion flow. As already noted in the introduction, this is not universally accepted, and a more complex picture is put forward by Wu et al. (2001, 2002) who argue for three distinct origins for the emission line depending on the source luminosity and spectral states. In all cases, the optical continuum and lines are likely to be excited by the irradiation from a central hot continuum source at least at high luminosities (see arguments in van Paradijs & McClintock 1994, and the more recent global study by Russell et al. 2006). As noted in the introduction, however, it has been suggested that the ionizing source may in fact be (at times) associated with an outflowing jet or corona and not necessarily a static central X-ray

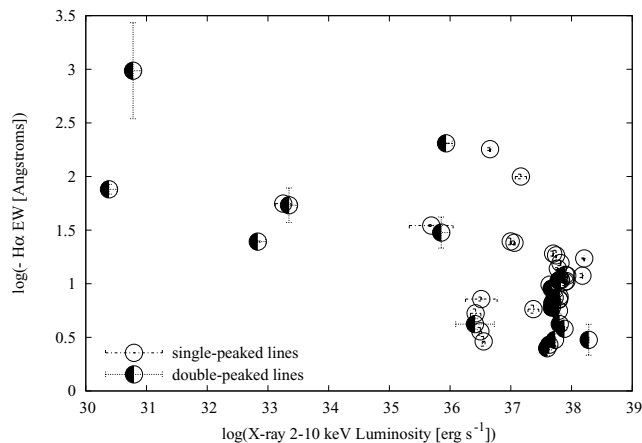
source (see e.g. Eikenberry et al. 1998; Beloborodov 1999; Markoff, Nowak & Wilms 2005). Although we do not think it has an important impact on this analysis, we note that double peaks may be filled in if the inclination is low or additional components produce low-velocity emission. Similarly, single-peaked profiles can also be mainly from a disc and vice-versa an intrinsic single-peaked profiles with central absorption could give the appearance of a double-peaked line without needing a disc-like flow.

The observed anticorrelation between  $H\alpha$  EW and X-ray luminosity (both direct and inferred) implies that as the X-ray luminosity decreases the optical continuum flux drops faster than the line flux. The analysis in Section 2.3 above demonstrates that, over large luminosity ranges at least, all three quantities (X-ray luminosity, optical luminosity and  $H\alpha$  line flux) are dropping, but at different rates (X-rays drop fastest, line flux slowest). The optical continuum in BHXBs appears to have contributions from both thermal emission from the outer, irradiated, accretion disc plus, in hard X-ray states, a component associated with optically thin synchrotron emission from a jet (Russell et al. 2006). The jet contribution is strongest at longer wavelengths, dominating in the infrared band, but probably contributes no more than 30 per cent of the luminosity in the *R* band (Corbel & Fender 2002; Homan et al. 2005; Russell et al. 2006), which contains the  $H\alpha$  line.

Note that at low luminosities the companion star may begin to have a discernible contribution to the continuum luminosity of the systems. Russell et al. (2006) compile the estimated optical luminosities of several X-ray binaries, and find that in most systems the companion only contributes significantly in quiescence (i.e.  $L_X \leq 10^{33}$  erg s $^{-1}$ ). Marsh, Robinson & Wood (1994) show how in the quiescent system, A0620–00, the  $H\alpha$  EW is modulated at the orbital period, presumably due to varying continuum contributions from the tidally distorted companion. We do not attempt in this paper to subtract such a contribution, noting that (i) over the range of luminosities covered in this compilation it is probably not a major effect and (ii) any contribution to the continuum by the companion would serve to *increase* the true disc EW at low luminosities and strengthen the anticorrelation where it is taken into account. However, it is worth noting that in a regime in which an approximately constant continuum level is set by the companion, the true line flux may be proportional to the measured EW.

### 4 DISCUSSION

Based on a wealth of observational data, we have an approximate picture of how the emitted spectra and, to a lesser extent, central accretion/outflow geometry might vary in BHXBs, principally, as a function of luminosity. For example, it is known that an approximately steady jet is produced at relatively low accretion rates ( $\dot{M}/\dot{M}_{Edd} \leq 0.01$ ) which are associated with hard X-ray spectra, whereas at higher accretion rates transitions to softer X-ray states with weaker jets can occur (Fender et al. 2004; Homan & Belloni 2005). At lower accretion rates, a simple relation between radio and X-ray luminosities appears to hold to at least  $L_X/L_{Edd} \sim 10^{-8}$  (Gallo et al. 2006). There is, however, some evidence that the X-ray spectrum does soften at very low luminosities (Corbel, Tomsick & Kaaret 2006; Corbel, Körding & Kaaret 2008). In the case of accreting white dwarfs in cataclysmic variables, Williams (1980) argued that the outer region of the accretion discs may at sometimes be optically thick in the line but thin in the continuum. If a similar situation exists during the decay phase of X-ray transients outbursts, it may well contribute significantly to the observed EW anticorrelation.



**Figure 7.** Observations in which twin-peaked  $H\alpha$  emission has been resolved. The detection of twin-peaked emission at all luminosities strongly suggests that the line always originates in a rotating accretion disc or optically thin accretion flow.



The observed anticorrelation is likely to be due to some combination of these changes in the accretion/outflow geometry, the irradiating spectrum and the optical depth in the outer accretion disc. A key question is whether or not there are changes in the line properties across the accretion state transitions. As noted earlier, this was one of the key motivations for this research; however, our findings are inconclusive. On the one hand, the line profile and EW of H $\alpha$  in GX 339–4 are clearly very similar in bright hard or soft states (Fig. 1), but the analysis in Section 2.1 suggests that the anticorrelation is better in the hard state below  $\sim 0.01L_{\text{Edd}}$ . Results for the BH transient GRO J1655–40 presented in Shrader et al. (1996) also suggest a large increase in H $\alpha$  EW across a soft  $\rightarrow$  hard state transition, although the soft X-ray luminosity of the source would also have been fading during this period. The reader is reminded that Wu et al. (2001) claim that the line profile changes from hard to soft X-ray states.

#### 4.1 Optical depth changes

A possible explanation for the observed anticorrelation is that a large part of the outer disc becomes cold enough to be optically thin in the continuum, not the line, during the decline (Williams 1980). In that case, the optical continuum drops much more quickly than the ionizing continuum from the inner region (where the inflow is still optically thick and producing strong continuum emission). As a result, the EW of the optical lines from the outer (optically thin) region should increase. Such optically thin regions of the outer disc may well exist in X-ray binaries (e.g. Canizzo & Wheeler 1984). Shahbaz et al. (2004) discuss the possibility of regions of different optical depth contributing to the H $\alpha$  and H $\beta$  emission from the BHXB A0620–00 in quiescence. It is also possible that there is a saturation effect, in that during outbursts most of the accretion disc becomes too hot for the production of H $\alpha$  line emission. The effect should therefore be different for higher excitation lines such as He II.

#### 4.2 Spectral and geometrical changes

Although the models mentioned above may well be responsible for the observed anticorrelation, studies over the past decade have indicated that the accretion flow in X-ray binaries, in particular, BH systems, undergoes dramatic changes on short time-scales which could well have an effect upon observed emission line profiles. For this reason, we summarize this empirical understanding below, and comment on whether or not it might affect the observed anticorrelation.

If, as we assume, the H $\alpha$  is a result of the irradiation of the outer disc, then the main source of this irradiation will be Extreme Ultraviolet (EUV) photons with energies between about 13 and 25 eV. These photons are not directly observable in nearly all BHXBs, which lie at several kpc in the Galactic plane and as a result suffer from strong interstellar extinction. Lower energy photons cannot ionize hydrogen, and photons with significantly higher energies (i.e. X-rays) are more likely to contribute to the reprocessed (reflection) continuum (e.g. Ross & Fabian 1993). We do not consider here the possibility of collisional excitation in, for example, an accretion disc hotspot.

How plausible is it that changes in the ionizing spectrum are responsible for the observed anticorrelation? In bright soft states ( $L_X \geq 0.01L_{\text{Edd}}$ ), the X-ray spectra of BHXBs are dominated by thermal (accretion disc) components with  $kT \geq 1$  keV. In less bright, but still very luminous ( $10^{-4}L_{\text{Edd}} \leq L_X \leq 10^{-2}L_{\text{Edd}}$ ), hard X-ray states,

the X-ray spectrum is dominated by a component which peaks at  $\sim 100$  keV and probably has its origin in a Comptonizing ‘corona’ (e.g. Sunyaev & Titarchuk 1980), with some possible contributions from a jet (e.g. Markoff et al. 2005). It should be noted that there can be strong hysteresis between spectral state and luminosity for  $L_X \gtrsim 10^{-2}L_{\text{Edd}}$  (Homan & Belloni 2005). As a source drops further in luminosity, the accretion disc temperature should drop monotonically until in ‘quiescence’ ( $L_X \sim 10^{-8.5}L_{\text{Edd}}$ ) it is only about 1 eV (McClintock, Horne & Remillard 1995; McClintock et al. 2003). As noted above, at most X-ray luminosities this thermal disc component is essentially unmeasurable as it peaks at (E)UV wavelengths, in which band most distant Galactic plane BHXBs cannot be observed. In the case of XTE J1118+480 (McClintock et al. 2003), this disc component was found to be significantly more luminous than the X-ray component when in quiescence. Therefore, at the lowest X-ray luminosities the bulk of the photons released by the accretion process are not able to ionize hydrogen, which – naively – should result in a reduced H $\alpha$  EW at the lowest luminosities, *contrary* to what is observed. However, the optical continuum is also dominated by reprocessing and so the overall effect on EW will depend upon which component is pumped most effectively by the ionizing continuum, which in some sense returns us to the models dealing with the optical depth of the outer disc (e.g. Williams 1980).

What about changes in the geometry of the accretion flow and outflow with luminosity? Some recent sketches of the accretion flow as a function of luminosity for BHXBs (Esin, McClintock & Narayan 1997; Done, Gierlinski & Kubota 2007) suggest that as luminosity increases the ability of the central hard X-ray source to illuminate the disc is reduced, as the coronal component shrinks. Geometries which include jets (e.g. Fender et al. 2004; Ferreira et al. 2006) may be more complete, although it is unclear how significantly any X-ray emission from the jet could contribute to the irradiation of the accretion disc or its atmosphere (Markoff et al. 2005). Such X-ray emitting regions near the base of the jet may be essentially indistinguishable from an outflowing corona (e.g. Beloborodov 1999). Nevertheless, it has been suggested that the velocity of the outflow from X-ray binaries may increase with luminosity, and in a more complex way with spectral state. If the jet or outflowing corona is responsible for some irradiation of the disc, then an increase in velocity with luminosity could result in a reduced H $\alpha$  EW as an increasing fraction of the X-rays are beamed along the direction of motion, away from the disc.

## 5 CONCLUSIONS

A prime motivation for this research was to investigate whether the profiles of optical emission lines change significantly across the accretion state transitions in X-ray binary systems. Such a result may have indicated a strong response to a changing irradiating spectrum and/or geometry of the line-emitting region. However, the results in this respect remain inconclusive.

What we did find, and report in detail, is an anticorrelation between the broad-band luminosity (optical–X-ray) and the EW of the H $\alpha$  emission line in X-ray binaries. Possibly the most closely related phenomenon already known is a comparable anticorrelation in the H $\beta$  line for cataclysmic variables (Patterson 1984; see also Witham et al. 2006), accreting binaries hosting a white dwarf rather than a BH or NS. Patterson (1984) compares this result with the models of Tylenda (1981), which are similar to those of Williams (1980) in which the outer accretion disc becomes optically thin at low luminosities. This may also turn out to be the appropriate explanation for the X-ray binaries under discussion here, but the

complex and hysteretical accretion state changes about which we have learned much in the past decade caution us against drawing such a conclusion at this time. More detailed observations of line profiles across state transitions would clearly be of interest. The reader is further reminded that (i) rebrightenings during the decay of transients, (ii) the monotonic behaviour of QPOs in sources such as XTE J1118+480 despite varying behaviour in  $L_X$  and (iii) the poorer anticorrelation of EW with quasi-simultaneous  $L_X$  than with time all suggest that the causal link between luminosity and EW may be complex.

It is worth mentioning in passing the similarity with the Baldwin effect observed in accretion flows around supermassive BHs (Baldwin 1977; see also e.g. Mushotzky & Ferland 1984). In this case, an anticorrelation is observed between the EW some lines originating in the broad line region (BLR) and the continuum luminosity. A related effect is observed in the X-ray band (Iwasawa & Taniguchi 1993; Page et al. 2004), and may be also in the strong stellar winds of Wolf–Rayet stars (Morris et al. 1993). However, there is little evidence for a BLR like region in X-ray binary systems, probably due to the high-ionization state of the gas in the inner disc region (e.g. Proga, Kallman & Stone 2000). Therefore, the physical origins of the two effects are almost certainly rather different.

Further observations would obviously be of interest to understand better this effect. These should include observations of other lines and in other bands. Observations in the near-infrared, where the continuum should have a much stronger jet contribution (e.g. Corbel & Fender 2002; Russell et al. 2006), should show a much stronger reaction to accretion state changes (e.g. we would expect a large jump in EW of a line like Br  $\gamma$  as the jet switches off in a hard  $\rightarrow$  soft state transition). It is interesting to note that the spectra in Fig. 1 hint at a similar anticorrelation for He I, and He II would be even more interesting, given the higher ionization potentials. The observed anticorrelation holds the promise of being able to estimate the luminosity of a source from the H $\alpha$  EW, something which could prove invaluable in distance determinations for faint X-ray binaries. However, the relation obviously needs to be significantly improved before that is possible, and may turn out to have enough intrinsic scatter to reduce its usefulness in this aspect (as is in fact the case for the Baldwin effect in AGN). In any case, it is promising that low-luminosity accreting sources should be clearly identifiable in, for example, H $\alpha$  surveys by their large EWs.

Finally, it is interesting to note that observations of the variation of the H $\alpha$  line strength with luminosity may in fact be our best way to track the behaviour of the accretion disc component at intermediate luminosities. Below  $L_X \sim 10^{-3} L_{\text{Edd}}$ , the accretion disc component peaks in the (E)UV spectral regime and is unobservable for nearly all sources. For two sources only has it been observed in quiescence, at which point it appears that it no longer extends to the Innermost Stable Circular Orbit (ISCO) but is truncated (McClintock et al. 1995, 2003). Although well-defined models exist (e.g. Dubus, Hameury & Lasota 2001), exactly how and where this truncation begins is observationally very uncertain (e.g. Miller et al. 2006). However, since the H $\alpha$  line responds preferentially to photons of energies 13–25 eV, it may be the best way to study the evolution of this disc component at luminosities  $10^{-6} \lesssim L_X/L_{\text{Edd}} \lesssim 10^{-3}$ .

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