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Hysteresis in the light curves of soft X-ray transients

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ABSTRACT

Using Proportional Counter Array (PCA) data from the *Rossi X-Ray Timing Explorer* (*RXTE*), we track the spectral states of the neutron star transient system Aql X-1 through a complete outburst cycle. We find a hard-to-soft state transition during the very early, rising phase of the outburst, and show that there is a hysteresis effect such that the transition back to the hard state occurs at a luminosity ∼5 times *lower* than the hard-to-soft transition. This hysteresis effect rules out the propeller mechanism as the sole cause of state transitions in Aql X-1. Assuming the propeller mechanism only operates at a luminosity equal to or below that of the observed soft-to-hard transition requires that the magnetic field of Aql X-1 be less than 7×10^7 G, the lowest neutron star field known to date. To compare the state transition behaviour of Aql X-1 with that found in transient black hole systems, we use *RXTE* All-Sky Monitor (ASM) data to compute hardness–intensity diagrams for four black hole candidate transients where the ASM data should also give us state information throughout much of the outburst cycles. In all four systems, we find evidence for a hard-to-soft state transition during the rising outburst phase and for the source staying in a soft state down to much lower luminosities during the declining phase, i.e. a hysteresis effect. This similarity suggests a common origin for state transitions in low magnetic field neutron star and black hole systems, and the hysteresis effect rules out the 'strong ADAF (advection-dominated accretion flow) principle' for determining the state of an accretion disc. We discuss the general implications of these observations for current models of state transitions. We note the contrast to previous observations of the non-transient systems Cygnus X-1 and X-3, which do not show a hysteresis effect.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual: Aql X-1.

1 INTRODUCTION

Soft X-ray transients (SXTs) represent a class of X-ray binaries that undergo occasional, perhaps quasi-periodic, outburst cycles during which their luminosities rise by factors of ∼100–10 000 (in the case of neutron star systems) to factors of $\sim 10^6$ or more (in the case of black hole systems). Their spectral states also change during these luminosity transitions. At the lowest luminosities for which the spectrum can be measured well, their continua generally look to be a hard ($\mathrm{d}N/\mathrm{d}E \sim E^{-1.5}$) power law, with a cut-off typically between 50 and 500 keV – the low/hard state. The low/hard state emission mechanism is generally thought to be thermal Comptonization by hot electrons (e.g. Sunyaev & Titarchuk 1980). At luminosities greater than about a few percent of the Eddington luminosity, the spectrum resembles, to first order, the standard multitemperature blackbody model of Shakura & Sunyaev (1973) – the high/soft state. In some cases, a 'very high state' exists where the multitemperature blackbody from the thin disc is seen at the same time as a hard power-law tail (albeit with a spectral photon index typically around 2.5) that extends to γ-ray energies with no apparent cut-off. The radiation mechanisms in the very high state are not as well understood as in the other states. There also exists an 'off state' at very low luminosities. Current observational evidence seems to favour the idea that the off state is merely an extension of the low/hard state to very low luminosities (see e.g. Corbel et al. 2000, hereafter C00), but the data are relatively sparse. For a review of the properties of the different spectral states, see Nowak (1995).

Past work has shown that the spectral state correlates with the system luminosity (see e.g. the reviews by Tanaka & Lewin 1995; Nowak 1995). In black hole systems, the spectral state transitions are currently thought to be driven by the shift in accretion flow geometry from a thin disc that extends to approximately the innermost stable circular orbit (high/soft state) to either a thin disc with a hole in it or a thin disc with a hot corona above it (the low/hard state). In this low/hard state, the hard X-rays are then thought to be produced by Compton scattering of these disc photons in a hot, quasi-spherical flow inside this hole (e.g. Shapiro, Lightman & Eardley 1976; Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994),

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by a magnetically powered corona above the disc (e.g. Nayakshin & Svensson 2001), or by the hot base of a relativistic jet [e.g. C00; see also Markoff, Falcke & Fender (2001), who claim the X-rays are synchrotron radiation from this jet].

To the extent that the accretion mode is determined only by the presence of a deep gravitational potential well, these models may apply to neutron star SXTs as well. However, neutron stars may possess significant magnetic fields and the 'propeller model' may be relevant in explaining the state transitions in some or all of these systems (e.g. Lamb, Pethick & Pines 1973; Zhang, Yu & Zhang 1998a; Campana et al. 1998). In the propeller model, the inner region is kept empty of mass by the magnetosphere of the neutron star when the magnetospheric radius is larger than the corotation radius, and hence the magnetic pressure of the magnetosphere is larger than the ram pressure of the gas. The neutron star then becomes very much like an isolated radio pulsar and the X-ray luminosity is then provided by some combination of a small fraction of the gas accreting along the magnetic poles and the collision of the pulsar wind with the accreting gas (Campana et al. 1998).

Until recently, the standard lore has held that the SXT outbursts usually proceed directly from quiescence into the high/soft state, perhaps going through a very high state first. This assumption has been recently contradicted by the observations of XTE J1550−564 (Wilson & Done 2001), XTE 1859+226 (Brocksopp et al. 2002) and Aql X-1 (Jain 2001), where hard states in the rising portions of the outbursts have been found. These initial hard states are not very long-lived, and it is only due to the advent of the *Rossi X-Ray Timing Explorer* (*RXTE*) All-Sky Monitor (ASM), which has greater sensitivity than previous all-sky monitors, to dedicated optical monitoring programmes (e.g. Jain 2001, and references within) and to the rapid response of the pointed instruments on the *RXTE* that detections of this brief hard state have been possible.

In this paper, we discuss *RXTE* light curves from the ASM and from the pointed Proportional Counter Array (PCA) of several soft X-ray transients: the neutron star system Aql X-1, and the black hole candidates 1748−288, 1859+226, 2012+381, XTE J1550−564 and GRO J1655−40 [see Liu, van Paradijs & van den Heuvel (2001, and references therein) for discussion of source identifications; see also Orosz et al. (2002) for a dynamical confirmation that XTE J1550−564 contains a black hole primary star; and see Fillipenko & Chornock (2001) for analogous work on 1859+226]. We show that, in all cases except 1655−40, the light curves seem to show hard states in the rising and falling phases of the outburst and hysteresis loops in diagrams of spectral hardness versus intensity. We discuss the implications for the different models of state transitions in SXTs. We note that the similarities between the outburst cycles could imply a common origin for the state transitions of black hole and neutron star SXTs and that a particular difficulty is presented for propeller models as the sole mechanism for state transitions in neutron star systems.

2 OBSERVATIONS

In general, hardness ratios of neutron star transients in the low/hard state cannot be well constrained by the ASM on *RXTE* because the source fluxes are too low. Fortunately, a full outburst cycle has been observed with the PCA for Aql X-1 by using ground-based optical monitoring from the Yale 1-m telescope (operated by the YALO consortium – see Bailyn et al. 2000) to trigger the series of target-of-opportunity X-ray observations we analyse here. [See Jain (2001) for a discussion of the optical observations.] Because the full-scale outbursts in Aql X-1 occur roughly once per year, and because the optical flux rises several days earlier than the X-ray flux, such a monitoring programme is feasible, effective and necessary in order to catch the rising phase of the X-ray outburst with pointed instruments. It is more difficult to get useful pointed observations of typical black hole transient sources in all spectral states – either they are new transients, in which case one does not know where to point the monitoring optical telescope, or they are recurring ones, but with substantially longer outburst cycles (typically ∼10 yr).

Aql X-1 is also an especially useful source for testing propeller models in neutron star systems because its spin frequency of 550 Hz has been measured as the coherent quasi-periodic oscillation (QPO) frequency in a Type I X-ray burst (Zhang et al. 1998b). Until recently, there had been some controversy as to whether the coherent QPO frequency represented the neutron star's spin frequency or twice its spin frequency. A series of five bursts from KS 1731−260 with coherent QPOs was examined to look for oscillations at $1/2$ and $3/2$ of the strongest coherent QPO frequency, and an upper limit on the power at these frequencies of 5 per cent of the power of the strongest frequency was found (Muno et al. 2000), making it extremely unlikely that the strongest frequency seen during the Type I bursts is actually a harmonic [although see Abramowicz, Kluzniak & Lasota (2001) for an argument *against* the claim that the coherent kilohertz QPOs show the rotational frequency of the neutron star].

For the black hole candidates, data from the ASM [see Levine et al. (1996) for an instrument description] are used. We take the ratio of counts at 5–12 keV (band 3) to counts at 1–3 keV (band 1) and construct a new hardness ratio. Since the typical disc temperature for a soft X-ray transient is about 1 keV (giving a spectral peak near 3 keV), the 1–3 keV band should be dominated by disc emission whenever a strong disc is present, and the 5–13 keV band should be well above the cut-off energy for the disc component. Thus this ratio should give a good indication of whether the accretion flow is in the hard state (where the νF_ν peak will be well above 10 keV) or in the soft state (where the νF_ν peak will be below 5 keV). An exception must be made in the case of GRO J1655−40. In this source, the disc temperature in the high/soft state can be quite large – up to a few keV (e.g. Sobczak et al. 2000). This can push the peak energy in the disc spectrum up past 5 keV (i.e. into the hardest band on the ASM) and can make any ratio of the count rates in two ASM bands a poor indicator of the spectral state. The ASM hardness ratios for GRO J1655−40 seem to scale with luminosity (i.e. the source becomes harder as it becomes brighter, because its disc temperature and disc flux are correlated), regardless of spectral state, consistent with these expectations, and thus indicating that the ASM cannot constrain the ratio of disc to power-law flux for this system. For XTE J1550−564, which has undergone three outburst cycles since the beginning of the *RXTE* mission (e.g. Smith et al. 2000; Jain et al. 2001), we plot the results from only the earliest (1998 late summer–early autumn) outburst, which is qualitatively similar to the plot for the other two outburst cycles. We further restrict the data sets by including only those days where the count rates in all three bands are positive (allowing for the construction of hardness ratios) and the net count rate in all three bands is greater than 1.5 count s^{-1}. The crude spectral measures from the ASM and the rather large uncertainties in the distances of the black hole systems will preclude accurate measurements of the luminosities of these systems from being made, but are sufficient for comparing relative fluxes for a given source.

The PCA data for Aql X-1 are extracted using the standard FTOOLS 5.0, using the standard *RXTE* Guest Observer Facility recommendations for screening criteria. The observations used are from the

1999 May/June outburst (proposal IDs 40047 and 40049). They are then fitted in XSPEC 11.0 using a thermal Comptonization model (EQPAIR) [see Coppi (1998) for a description of the model]. The details of the spectral fitting procedure and the results of the spectral fits will be described in a follow-up paper (Maccarone & Coppi 2002). The essence of the procedure that is relevant to this work is that: (1) by fitting a model, we may accurately estimate the flux from the source; and (2) the model returns as a fitting parameter the ratio of luminosity in the Comptonizing electrons to the luminosity in the disc, which indicates the spectral state of the system.

3 RESULTS

For Aql X-1, we plot flux versus the ratio of Comptonizing electron luminosity in the corona to disc luminosity in Fig. 1(a). Arrows trace the outburst cycle from earliest time to latest time. To facilitate comparisons with the black hole systems, we also plot, in Fig. 1(b), the Aql X-1 data converted into ASM units. We make this conversion by dividing the ASM model counts by the Crab model counts (as given in Wilms et al. 1999) in the two energy ranges (1–3 keV and 5–12 keV) and then multiplying the resulting ratios by the Crab count rates. Since the Crab ratios do not strictly represent a response matrix, slight systematic errors may be introduced in this way. Additional systematic errors may be introduced by the extrapolation of the best-fitting model for Aql X-1 to energies below the range where the fit was made. None the less, this figure should make it easier for the reader to see the qualitative similarities between the black hole and neutron star systems. The figures look essentially the same, with one exception – the compactness monotonically decreases early in the Aql X-1 outburst cycle, but the hardness increases for the first few points. This time period corresponds to an increase in the best-fitting seed photon temperature, which pushes the peak of the accretion disc's spectrum from the lowest ASM channel to the middle ASM channel. When the temperature is low and the disc's spectrum is peaking in the lowest channel, the ratio of counts in band 3 to counts in band 1 is lower for a given ratio of disc luminosity to corona luminosity than it does when the disc spectrum peaks in the second ASM channel.

In Aql X-1, the observed transition from hard state to soft state occurs at a flux level of 4.2–5.5 × 10^{36} erg s^{-1}, assuming a distance of 2.5 kpc (Chevalier et al. 1999), while the transition from the soft state back to the hard state occurs at 6.1–7.5 × 10^{35} erg s^{-1}; that is to say, the ratio of luminosity in the hard component to luminosity in the soft component remains roughly constant from the onset of the soft state until the return to the hard state a factor of 5–10 lower in luminosity. The possibility of hysteresis behaviour in Aql X-1 has been pointed out based on observations of the system at a higher luminosity in the hard state of one outburst cycle than in the soft state of another outburst cycle (see e.g. Cui et al. 1998; Reig et al. 2000), but the effect is shown here definitively for the first time. Some additional previous evidence for hysteresis has been seen in other sources: steadily accreting neutron stars have shown signs of hysteresis in the transitions between island and banana states (Muno, Remillard & Chakrabarty 2002); the candidate microquasar XTE 1550−564 shows brief interludes where its spectral and variability properties seem to resemble those of the very high state, but without its luminosity rising above the typical luminosity in the high/soft state (Homan et al. 2001); the black hole candidate GX 339-4 shows a very similar hysteresis effect in its state transitions between the low/hard and high/soft states (Grebenev et al. 1991; Miyamoto et al. 1995; Nowak 1995; Nowak, Wilms & Dove 2002); and several persistently bright low-mass X-ray binaries containing black holes have shown different luminosities for the hard-to-soft and soft-to-hard state transitions (SHS).

The results from the ASM work on the black hole systems are plotted in Fig. 2. We note that analogously to the case of Aql X-1, the hardness ratios of the black hole systems remain roughly constant over a drop by a factor of ∼10 in count rate. Like the inferred ASM rates for Aql X-1, all four figures span three decades in count rate and two decades in hardness ratio. Since the count rates for 1859+226 and 2012+381 are similar to the count rates for Aql X-1, these three sources are all plotted for the same range of hardness and count rate values, so their curves are not centred in the graphs. The only major difference is that Aql X-1 is somewhat harder than the two black hole sources at all count rates, but this offset is roughly constant as a function of count rate, and we cannot be sure whether it is a real effect or is an artefact of the process by

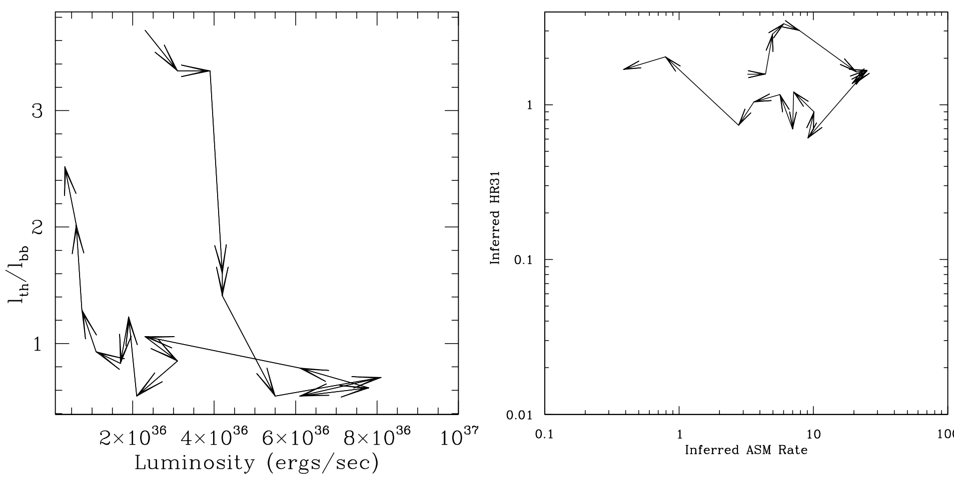

Figure 1. Left: The luminosity of Aql X-1 in erg s^{-1} plotted versus the ratio of the luminosity of the corona to the luminosity of the disc. The errors are left unplotted in order to avoid confusing the plot, but are typically about 0.1 for ℓ_{th}/ℓ_s and about 1 per cent for the luminosity. Right: The inferred ASM count rate (all bands) plotted versus the inferred ASM hardness ratio, (Counts from 5–12 keV)/(Counts from 1–3 keV), for Aql X-1. The conversion is done to allow an easier comparison with the black hole data in Fig. 2. In both plots, the arrows trace the outburst as a function of time.

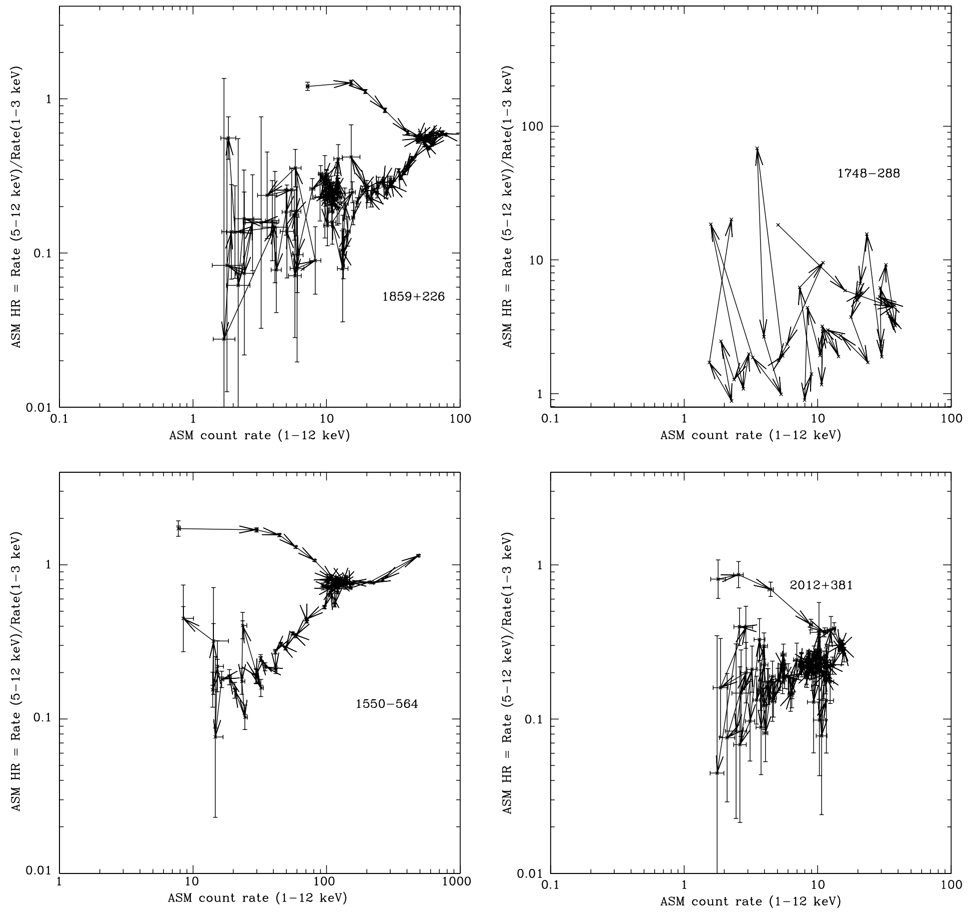

Figure 2. ASM count rate versus hardness ratio for the four candidate black hole transients. The arrows trace the outbursts as a function of time.

which we have inferred the ASM count rates from the PCA. Because the hardness ratio is roughly constant, the conversion from count rate to luminosity should also remain roughly constant. Often the transition from soft-to-hard cannot be seen because, by the time the transition is made, the flux level has dropped below the threshold of 1.5 count s^{-1}, and the hardness ratios are hence unreliable as a result of the poor statistics. Thus we cannot be certain that the state transition that occurs is to the 'low/hard' state rather than to the 'off' state, but, as noted above and in C00, there is no evidence for substantial differences in properties between the low/hard and off/state; the off state has generally been defined based on source luminosities being lower than instrumental thresholds and not based on any spectral transition or rapid luminosity change from the low state. Arrows trace the outburst cycles from earliest time to latest time. The errors are left unplotted for XTE J1748−288; because this source lies in a high background region towards the Galactic Centre (Revnitsev et al. 2000), the errors for this source are quite large and plotting them severely confuses the figure. Thus conclusions about 1748−288 should be weighed accordingly. We plot the results none the less because they seem qualitatively similar to the other three sources for which good ASM light curves can be made.

4 DISCUSSION

4.1 Connection with previous hysteresis observations

Hysteresis results have previously been noted for several X-ray binary black hole systems that are not classical transients because they never enter the off state (Smith, Heindl & Swank 2002, hereafter SHS). The power-law indices of these sources were compared with their photon fluxes. For the low-mass X-ray binary systems, the hardening of the power-law components was found to lag behind the drop in brightness. Such behaviour is qualitatively similar to what we have observed in the classical transients.

The high-mass X-ray binaries in the SHS sample, Cygnus X-1 and Cygnus X-3 do not fit this trend. It has been shown that, for both these systems, the *RXTE* count rate and spectral index track one another with only short time lags (SHS). SHS thus suggest that the hard and soft components of the spectra are caused by two different accretion flows [a picture similar to that invoked by van der Klis (2001) to explain properties of quasi-periodic oscillations], and that the difference between the two Cygnus systems and the other X-ray transients is caused by the high-mass nature of the mass donor. Since wind-driven accretion tends to form smaller accretion discs, disturbances should pass through the discs more quickly. Changes in the hard X-ray accretion flow (the corona) occur quickly in all systems, while changes in the soft X-ray flow (the disc) occur on a time-scale of the order of the viscous time-scale of the accretion disc. The accretion discs are larger in the low-mass systems than in the high-mass systems, so the viscous time-scales might be expected to be longer in the low-mass systems.

We note, however, that the 'soft' state of Cygnus X-1 is not a typical soft state, as it has a rather substantial hard X-ray tail, probably related to Comptonization of non-thermal electrons (see e.g. Gierliński et al. 1999). Furthermore, it occurs at a luminosity probably not much higher than the low/hard state luminosity (see e.g.

Frontera et al. 2001), and the bolometric luminosity changes in Cygnus X-1 are, in fact, never very large. As we discuss below, the hysteresis effect could in part reflect the radical, non-equilibrium nature of a transient outburst, particularly during the rising phase. Cygnus X-1 never experiences such violent changes.

We note that the case of Cygnus X-3 is likely to be unique. Given that the most likely distance estimate of 11.5 kpc implies that Cygnus X-3 has a minimum luminosity of $\sim 2 \times 10^{38}$ erg s^{-1}, that its strong radio flares correspond with strong X-ray flares (Mioduszewski et al. 2001), and that archival Green Bank Interferometer data show that the radio flux from Cygnus X-3 in the 2.3 and 8.3 GHz bands never drops below 20 mJy for more than a few days at a time over the $\sim$4 yr of public data, we conclude that Cygnus X-3 is likely to be in the very high state at all times. Its spectral state changes are thus more likely to be like those in GRS 1915+105 (see e.g. Belloni et al. 2000) than those of Cygnus X-1 or of the soft X-ray transients. It would thus be beneficial for us to observe some high-mass X-ray binaries which go through the classical set of state transitions before evaluating whether the 'two accretion flow' scenario is correct. At present no such systems are known in the Galaxy, and for theoretical reasons it *may* be that no wind-driven soft X-ray transients can exist.

4.1.1 Comparison with GX 339-4 radio/X-ray results

A phenomenological similarity exists between the results found here and the hysteresis diagram of radio flux versus X-ray flux for GX 339-4 found in C00. That plot shows that the radio flux is strong and correlated with the X-ray flux during the hard state, falls as the X-ray flux rises in the transition state, and is unobservable during the high/soft state. The X-ray flux then falls during the soft state, while the steady radio flux remains quenched. The source sometimes then enters an off state where it is undetectable in X-rays and in radio, but sometimes proceeds directly back into the low-luminosity end of the hard state. The hard-to-soft transitions always occur at higher luminosities than the soft-to-hard or soft-to-off transitions. It has been noted elsewhere that the hard-state luminosities of GX 339-4 sometimes exceed its soft-state luminosities (e.g. Nowak et al. 2002; Kong et al. 2002). While GX 339-4 shows all the spectral states of X-ray transients, it is not usually considered a classical soft X-ray transient because it frequently spends long periods of time in the hard state and does not always go into the off/quiescent state in between high-state episodes. Still, the fact that its outburst cycles also show hysteresis loops suggest that the phenomenon is present in X-ray transients of all kinds. Furthermore, that the radio emission is completely quenched in the soft state suggests that no persistent outflow is occurring in the soft state. This provides additional, albeit indirect, evidence that the wind in the soft state of Aql X-1 is likely to be weak, if present, since strong outflows generally show some radio emission. The analogies between GX 339-4 and the more standard transient sources also underscore the need for relatively deep radio monitoring data on the soft X-ray transients. While many of these sources are monitored in the radio by the VLA (and were monitored by the Green Bank Interferometer), the observations so far have generally not been deep enough to make detections (M. Rupen, private communication). We note that we have tentative evidence for a 0.2-mJy detection of Aql X-1 as it enters the low/hard state in the 2002 outburst (Maccarone et al. 2002, in preparation). It is still not clear whether these observations indicate that the jet/outflow is supplying the X-rays, as suggested by C00 (see also Markoff et al. 2001), or that the jet has a power proportional to the X-ray luminosity and only turns on when the accretion flow is geometrically thick (see e.g. Meier 2001).

4.2 Implications for propeller models and the magnetic field of Aql X-1

The similarities between the outburst cycles of the neutron star system Aql X-1 and the black hole systems are quite striking. The simplest conclusion is that the same mechanism drives the state transition in both accreting black holes and accreting neutron stars. This in turn casts serious doubt on propeller models for the state transitions in Aql X-1, which to date has been one of the strongest candidates for showing this effect (Zhang, Yu & Zhang 1998a, hereafter ZYZ; Campana et al. 1998). According to ZYZ, the propeller effect becomes important at a critical luminosity, determined by the magnetic field and the rotation rate of the neutron star, properties that remain nearly constant throughout a single outburst cycle. Under these assumptions the propeller model can be unequivocally ruled out as the sole cause of state transitions based on these observations. In the derivation of the critical propeller luminosity (Lamb et al. 1973, hereafter LPP), it is shown that it is the ram pressure and hence the accretion rate itself that is the critical factor, not the luminosity. Thus if one posits a strong wind inside the magnetospheric radius only after the soft state has started, then one can keep a high ram pressure at the magnetospheric radius while reducing the flux of mass that reaches the surface of the neutron star and hence reducing the luminosity of the accretion flow. Still no current models exist to explain how such an outflow would occur, and, even given such a model, the difficulty of explaining the very similar black hole state transitions with a qualitatively different model would remain. In fact, most current theoretical work suggests that outflows should be more important in the low/hard state than in the high/soft state (see e.g. Blandford & Begelman 1999).

Having established that standard propeller effects can cause only the soft-to-hard transitions (and then only possibly), we can place an upper bound on the magnetic field strength by finding the critical magnetic field needed for propeller effects to be important:

$$B_9 = P_{-2}^{7/6} M_{1.4}^{1/3} R_6^{-5/2} L_{\mathrm{X},36}^{1/2}, \tag{1}$$

where $L_{\mathrm{X},36}$ is the X-ray luminosity in 10^{36} erg s^{-1}, B_9 is the surface magnetic field in units of 10^9 G, P_{-2} is the spin period in units of 10 ms, $M_{1.4}$ is the neutron star mass in units of 1.4 solar masses, and R_6 is the radius of the neutron star in units of 10 km (LPP; ZYZ). Setting L_X to 6.1×10^{35} erg s^{-1} (the lower bound for the soft-to-hard state transition), the radius to 10 km, the mass to 1.4 $\mathrm{M}_\odot$ and the period to 1.8 ms (as given by the 550-Hz quasi-periodic oscillation), we find that the magnetic field must be less than 7×10^7 G. In fact, the magnetic field would only be this large if the soft-to-hard state transition is caused by the propeller effect; if it is not caused by propellers, then the field could be arbitrarily small. Explaining the hard-to-soft state transition with propeller effects would require a magnetic field of about 2×10^8 G.

An additional problem apart from the necessity of a wind in the soft state arises from explaining both transitions with the propeller effect – the magnetic field of the neutron star will then exceed its equilibrium value, in contradiction to generally accepted models of millisecond pulsar evolution (e.g. Srinivasan 1995). If one replaces the instantaneous luminosity in equation (1) with the mean luminosity, then the equilibrium magnetic field (i.e. the magnetic field where the spin-up due to accretion and the spin-down due to magnetic braking are in equilibrium) results (Bhattacharya 1995). Given the mean luminosity for Aql X-1 of $\sim 5 \times 10^{35}$ erg s^{-1} as estimated from the ASM count rates, a 1.8 ms period from the 550-kHz QPO, and the canonical values for the other parameters, the equilibrium magnetic field would be 6×10^7 G, far less than the 2×10^8 G field needed to cause the hard-to-soft transition.

A quick timing analysis has shown that there are no coherent pulsations at 550 Hz in the *RXTE* data down at the level of ∼2 per cent in the two low-state observations that occurred after the soft-to-hard transition. This provides potentially strong evidence that the propeller effects are not likely to cause the state transitions in Aql X-1. This observation is not definitive, though, because the intrinsically narrow QPO from matter falling along the magnetic poles may be broadened in time by the bulk Comptonization that causes the X-ray spectrum in the propeller state to be hard. The magnetospheric radius of Aql X-1 is at least 500 km, since the state transition luminosity is no more than 7.5×10^{35} erg s^{-1}. Since the bulk Comptonization will occur mostly outside the magnetospheric radius (and should not be in the extreme Klein–Nishina limit where forward scattering dominates), the initially coherent pulses will be smeared out by the Comptonization. Since the light traveltime though the magnetosphere is longer than the pulse period, this smearing effect could be sufficient to make the coherent QPOs unobservable in the hard X-ray bands of *RXTE*. A future timing mission with better soft X-ray coverage, such as the proposed timing mission for *XEUS* (Barret et al. 2002), could make a more definitive statement based on the lack of pulsed emission.

Propeller effects might still be important at lower accretion rates such as those which put the source in quiescence (e.g. Menou & McClintock 2001) and hence with Aql X-1 having a lower magnetic field than that claimed by ZYZ and by Campana et al. (1998). In fact, given that the mean L for Aql X-1 is very close to the L at the transition from soft state to hard state (and hence if the source is in equilibrium, the propeller effect's critical mass accretion rate is close to the soft-to-hard transition accretion rate), the propeller effect may set in very shortly after the transition from soft state to hard state, or it may even cause the soft-to-hard state transition to occur at a slightly higher accretion rate than would occur in the absence of a magnetic field. If, however, the neutron star is still spinning up, then the magnetic field must be lower than the equilibrium value of 6×10^7 G. Such a magnetic field value would be lower than any other measured neutron star magnetic field [see Cheng & Zhang (2000) for a list of pulsar magnetic fields], which should not be too surprising, since few pulsars have frequencies as fast as the 550 Hz frequency of Aql X-1.

Magnetic screening by accreted material on the surface of a neutron star has been suggested as a mechanism for finding an inferred magnetic field lower than the actual surface value, but has been found to be important only for accretion rates above ∼1 per cent of the Eddington luminosity (Cumming, Zweibel & Bildsten 2001). Since the luminosities here (both for the soft-to-hard state transition and for the mean luminosity) are well below that value, magnetic screening is unlikely to be important. If the mean luminosity of Aql X-1 in the past ∼100–1000yr has been substantially (i.e. about five times) higher than the average over the *RXTE* mission lifetime, magnetic screening could be important.

4.3 Implications for advection-dominated flows

Outburst cycles in the advection-dominated accretion flow (ADAF) picture are also often explained in terms of disc instability models (e.g. Menou et al. 2000). The triggering of an outburst due to the disc instability and the change from an advection-dominated flow to a thin disc need not happen at the same accretion rate. Despite the claim in the standard picture that the state changes depend only on the accretion rate (e.g. Esin, McClintock & Narayan 1997), it is likely that, in the ADAF picture, some sort of hysteresis would occur. Advection (at low luminosities) occurs when the mass density is too low for electrons and protons to exchange energy efficiently through Coulomb interactions. When the accretion flow is geometrically thick, the mass density and hence the interaction rate between electrons and protons are reduced compared to when the accretion flow is geometrically thin. Thus the critical accretion rate below which the disc must drop to become a geometrically thick ADAF should be smaller than the critical accretion rate above which the ADAF must collapse into a thin disc. In fact, the work of Zdziarski (1998) shows that the luminosity of the state transitions should be approximately $0.15y^{3/5}\alpha^{7/5}L_{\rm Edd}$, where $y = (4k_{\rm B}T/m_{\rm e}c^2){\rm Max}(\tau, \tau^2)$. Thus barring a large increase in α during the soft state, the hard-to-soft transition should be expected to occur at a higher luminosity than the soft-to-hard transition, since y will be higher in the hard state than in the soft state.

Three possible scenarios have been outlined for determining whether a system will enter an advection-dominated flow: the 'strong ADAF principle', which states that a system will enter an advection-dominated flow whenever such a solution is possible; the 'weak ADAF principle', which states that the ADAF will be chosen whenever it is the only *stable* solution possible; and the 'initial condition principle', which states that the initial conditions determine which solution will be chosen (Narayan & Yi 1995; Svensson 1999). The observations of hard spectra at the high accretion rates seen in the rising portion of the low/hard state imply that advection-dominated flows are possible (if they do, indeed, describe the hard states) at the luminosities where the system is seen in the soft state in the decaying phase of the outburst. This provides a clear rejection of the strong ADAF principle. It is likely that the system is stable in the soft state where the luminosity is dropping, because the luminosity is changing rather slowly here. It *may* be unstable in the rising portion where the luminosity is changing rapidly, and may hence be pushed into a spectral state it would not enter if the luminosity changes were slow. Thus either the 'weak ADAF principle' may apply, if ADAF solutions are stable when the disc luminosity is changing rapidly, but thin disc solutions are not stable to rapid luminosity changes, or the initial condition principle may apply. In fact, the standard ADAF may be unstable itself (Blandford & Begelman 1999). Whether the specific hot adiabatic accretion flow in the hard state is the ADAF picture or one of the scenarios with outflows or convection is beyond the scope of this paper.

4.4 Disc evolution and evaporation?

A possible picture to explain how the initial conditions affect the spectral state is that, when the accretion rate shuts off at the end of the outburst, the system stays in a disc-dominated flow until the disc is evaporated into the corona (e.g. Mineshige 1996; Cannizzo 2000; Meyer, Liu & Meyer-Hofmeister 2000; Dubus, Hameury & Lasota 2001). The observed hysteresis effect may then be a result of the time between when the evaporation dominates over disc inflow (i.e. when the system begins filling the corona with gas) and when the corona dominates the total energetics of the system (i.e. when the corona becomes filled). The fraction of the accretion flow that is pumped into the corona and the disc may depend only on the accretion rate, but the state of the system will depend also on the recent history of the accretion flow. The inner disc will fill in as it accretes matter from the disc at larger radii, but the inner disc will empty by dumping matter into the corona. Since the matter follows a different geometric path on its way into and out of the disc, hysteresis might be expected. This picture has already had some success in explaining the fast-rise exponential decay light-curve profiles for the outbursts of X-ray transients (Cannizzo 2000). Numerical modelling is currently under way to determine whether this picture can match the quantitative details of the observations (J. Cannizzo, private communication). In essence, in this picture, this disc can fill in much more rapidly than it can be evacuated by evaporation or other means. Such a scenario might also be able to explain the results seen in Cygnus X-1, where, as noted by SHS, the disc is likely to be smaller, and where the luminosity changes are also smaller, indicating that the system is not as severely perturbed from the steady state. In essence, the class of models where the rates of disc filling and evacuation determine the properties of the accretion flow solution is a realization of the 'initial condition principle'. When the system is changing rapidly, as in the outburst, it may enter into non-steady-state regions of phase space where an ADAF is supported at relatively high accretion rates. When the system is changing slowly, as in the decline, or in systems like Cygnus X-1 where the luminosity is nearly constant over the outburst, these regions of phase space are not accessed.

Other evidence for initial conditions affecting the accretion flow on rather long time-scales has been seen in the parallel tracks of luminosity versus QPO frequencies seen in several low-mass X-ray binaries (van der Klis 2001). In this picture, the only important initial condition is the time-averaged luminosity. The key feature is that there are two accretion flows, one radial and one disc-like. The radial flow is assumed to be a constant fraction of the disc flow, but to be averaged over the accretion rate in a large annulus of the disc. The radial flow propagates inwards more quickly than does the disc flow, so changes in the overall accretion rate are manifested in the radial flow before they are manifested in the disc-like flow, and, mathematically, it can be represented as a time average of the future disc-like accretion rate. The total luminosity is then the disc luminosity plus the radial flow's luminosity. The quasi-periodic oscillation frequencies then are assumed to vary as a function of the instantaneous accretion rate divided by the mean luminosity. Thus parallel tracks are formed because the disc luminosity varies much more quickly than the radial flow luminosity. The increase of frequency with luminosity on short time-scales comes from the fact that only the disc luminosity changes on short time-scales. The parallel offsets of the tracks come from changes in the radial component's contribution to the luminosity.

Our data challenge this specific two-flow picture. In the Aql X-1 data, where the soft-to-hard state transition is well observed, the state transition is rapid compared to the decay; after about 20 d of steadily dropping luminosity in the high/soft state, the spectrum goes from a high optical depth and a low compactness to a low optical depth and high compactness in 2 d. If the radial flow, which makes up the hard component, represents a time average of the future disc luminosity, then the transition from the soft state back to the hard state should not be rapid for an outburst that decays slowly in luminosity, and one would expect the source's spectrum to harden quite gradually. This picture has success in predicting the properties of the quasi-periodic oscillations, however, and should not be rejected too hastily. The best test of this model, tracking the QPO frequencies through the outburst so that the time-averaged luminosity can be measured directly and compared with the QPO frequencies, is not easily accomplished; the QPOs are not strong enough to be seen in all these Aql X-1 observations, most likely because not all the proportional counters are turned on for all the observations and some of the exposures are rather short. The scenario of van der Klis (2001) might be modified by making the radial-to-disc accretion ratio a function of the luminosity, which presumably becomes a steep function around the state transition luminosity. It then becomes essentially similar to the disc evaporation picture described above, with the added feature of explaining the quasi-periodic oscillation frequencies.

5 CONCLUSIONS

We find that, for soft X-ray transients with a neutron star primary (Aql X-1), and four soft X-ray transients with black hole candidate primaries (certainly XTE J1550−564, J1859+226 and J2012+381, and probably XTE J1748−288), plots of spectral state versus luminosity show hysteresis loops. In all cases, hard states are seen in the rising phases of the outburst cycle. The luminosity of the hard-to-soft transition is generally a factor of ∼5 or more brighter than the soft-to-hard transition. The observation for Aql X-1 suggests that the turning-off of the propeller effect cannot cause the state transition from the hard state to the soft state. The magnetic field of the neutron star in Aql X-1 can be constrained to be $< 7 \times 10^7$ G, a lower value than that for any other known neutron star. The similarities between the outburst cycles in neutron stars and black hole candidates suggest a common state transition mechanism. Three promising possibilities are: (1) the state transition luminosity from an adiabatic accretion flow to a thin disc is higher than the transition luminosity from a thin disc to an adiabatic flow because interactions are more efficient in the thin disc where the mean particle separation is smaller; (2) during the rapid luminosity rise, a geometrically thin accretion flow is not stable, so the geometrically thick flow persists because the system is out of equilibrium; and (3) a time lag is present in the transition from thin disc to geometrically thick accretion flow because the disc must be evacuated or evaporated. Given the present data and the present state of theoretical work, we cannot distinguish among these possibilities. The analogous hysteresis properties of the radio and hard X-ray fluxes of GX 339-4 lend some credence to the idea that the effects of jets may be of some importance. Observations of the full series of spectral states of additional neutron stars may determine whether the soft-to-hard state transitions may be routinely caused by propeller effects, and hence whether the similarity between the mean luminosity and the soft-to-hard transition luminosity is a coincidence or is due to the soft-to-hard state transition being caused by propeller effects. Better monitoring of soft X-ray transients at radio wavelengths is also necessary to improve our understanding of what role jets may play in the production of the hard X-rays.

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