A Hard-to-Soft State Transition during a Luminosity Decline of Aquila X-1

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\textbf{ABSTRACT}

Contrary to the idea that the X-ray spectral states of accreting black holes and neutron stars are determined by the mass accretion rate and that a transition from the low/hard (LH) state to the high/soft (HS) state is associated with an increase of luminosity, we have discovered a hard-to-soft state transition during a luminosity decay of Aquila X–1 in the observations made with the Rossi X-ray Timing Explorer (RXTE). The 2–60 keV energy flux corresponding to the state transition is $9.3 \times 10^{-10}$ ergs cm$^{-2}$ s$^{-1}$, an order of magnitude lower than the maximum observed in the past. The 2–60 keV peak flux of the following HS state is $1.5 \times 10^{-9}$ ergs cm$^{-2}$ s$^{-1}$. This confirms the correlation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state previously found. The relation derived from the observations of four outbursts is consistent with a linear relation over a luminosity range of an order of magnitude. This implies that the luminosity of the hard-to-soft state transition is not determined solely by the mass accretion rate, but appears determined by the peak luminosities of the soft X-ray outbursts. The time lag of the peak of the HS state relative to the occurrence of the hard-to-soft state transition varied from about 5 days to 11 days, showing a weak trend of increasing time lag with increasing peak luminosity of the HS state. These results provide additional evidence that the mass in the accretion disk probably determines the luminosity of the hard-to-soft state transition.

\textit{Subject headings:} accretion, accretion disks — black hole physics — stars: individual (Aquila X–1, 4U 1705–44, GX 339–4, XTE J1550–564)

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1. Introduction

The low/hard (LH) state and the high/soft (HS) state are the two main X-ray spectral states identified in the Galactic black hole binaries (see the review by McClintock & Remillard 2005 and references therein). Similar spectral states, namely the island state and the banana state (Hasinger & van der Klis 1989), have been seen in the atoll sources in the neutron star low-mass X-ray binaries (LMXBs) (e.g. van der Klis 1994; Barret & Vedrenne 1994). The state transitions between the two states are also similar in terms of the X-ray energy spectra and variability properties (e.g. Yu et al. 2003). These observational properties suggest that the same physics is involved in both black holes and neutron stars during the state transitions between the two states.

Mass accretion rate has long been thought to determine the spectral state of an accreting black hole or neutron star, thus the variation of the mass accretion rate was thought to cause the transitions between the states (e.g., Esin et al. 1996). When the mass accretion rate is low, a source stays in the LH state and has a relatively low luminosity. The energy spectrum is hard, with a power-law spectral shape and a hard tail extending up to several hundred keV. When the mass accretion rate is high, a source stays in the HS state. The energy spectrum is soft, showing a thermal emission probably originated from the accretion disk. In the case of neutron star accretion, X-ray emission may also come from the neutron star surface or boundary layer.

However, recent observations show that mass accretion rate is not the only parameter that determines the spectral states (Homan et al. 2001; Smith, Heindl, & Swank 2002; Yu, van der Klis, & Fender 2004). Suggestions for possible causes include (1) corona size (Homan et al. 2001); (2) a two flow accretion geometry which leads to the idea that the size of the accretion disk affects the state transitions (Smith, Heindl, & Swank 2002); (3) past history of the location of the inner edge of the accretion disk with state transitions (Zdziarski et al. 2004); (4) the mass in the accretion disk (Yu, van der Klis, & Fender 2004, here after YKF 2004).

The suggestion that the mass in the accretion disk affects state transitions is based on the correlation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state in the observations of two outbursts in each of the transients Aql X–1, XTE J1550–564 and a quasi-persistent neutron star LMXB 4U 1705–44 (YKF 2004). The correlation indicates that the higher the luminosity of the hard-to-soft state transition, the brighter the following HS state will be. Because the outbursts have similar durations, a brighter outburst is associated with an accretion of more mass onto the compact object. The correlation also suggests that the earlier accretion flow that powers the LH state and the later accretion flow that powers the HS state are somehow related, suggesting that
the outer disk contributes to the generation of the hard power-law spectral component which dominates the X-ray radiation in the LH state (Yu 2006). There is additional evidence that the hard, power-law spectral component is associated with the mass in the disk. In the black hole transient GX 339−4, the peak fluxes of the LH states in the seven outbursts seen by BATSE and HEXTE in the past 15 years is nearly linearly related to the outburst waiting time (Yu et al. 2006).

In this paper, we report our study of four outbursts in which the peaks of the LH states in the outburst rises and the following HS states were covered by RXTE observations. Especially noteworthy, we have identified a hard-to-soft state transition during a decline of the LH state in a very faint outburst in 2001. This outburst is actually fainter than the 2005 outburst, which was a hard state outburst candidate, observed by the RXTE and the INTEGRAL (Rodriguez, Shaw, & Corbel 2006). The peak ASM count rate was around 5 c/s, while the transition occurred at a count rate below 1.5 c/s (1 σ upper limit). We also show that these observations establish a nearly linear relation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state over a luminosity range of an order of magnitude.

2. Observations and Analysis

All of the public RXTE observations of Aql X−1 until June 2006 were used to search for the hard-to-soft state transitions. As the first step, we have analyzed the RXTE standard products and the RXTE/ASM light curve of Aql X−1 following the method described in YKF (2004). We have generated the hardness ratios between the HEXTE (15–250 keV) count rates and the PCA (2–9 keV) count rates. The hardness ratios clearly show the LH states and the HS states that Aql X−1 stayed. The LH states and the HS states correspond to a hardness ratio around 0.3 and 0.02, respectively. The distinct hardness ratios help identify the time windows corresponding to the occurrence of the hard-to-soft state transitions as well as the soft-to-hard state transitions in the outburst decay.

The observations of Aql X−1 around these state transitions were performed roughly once every two days. Thus the time windows corresponding to any hard-to-soft state transition is accurate to about one day. In four outbursts of Aql X−1, we have identified the observations of the LH states corresponding to the starts of the hard-to-soft state transitions. These observations were made on MJD 51316, 51820, 52095, and 53162, which were selected by the criteria that their HEXTE (15–250 keV)/PCA (2–9 keV) hardness ratios are above 0.2 and they are immediately followed by the transition, i.e., a drop of the harness ratio to 0.02. The observation IDs are 40047-01-01-00, 50049-01-04-03, 60054-02-02-04, and 90017-01-09-01.
We have marked the data points in these observations as squares in the 2-day averaged light curves of the ASM, the PCA (2–9 keV), and the HEXTE (15–250 keV) in Fig. 1. Similarly, we have also identified the observations of the corresponding peak HS states by selecting the peak PCA (2–9 keV) count rates after the state transitions. These peak HS states occurred on MJD 51324, MJD 51831, MJD 52102, and MJD 53167, and are marked as diamonds (Fig. 1). The corresponding observation IDs are 40047-02-03-01, 50049-02-03-01, 60054-02-03-05, and 90017-11-01-00. We have identified a hard-to-soft state transition around MJD 52095 during a decay of a LH state in a faint outburst of Aql X−1. The luminosity decreased in the LH state before the hard-to-soft state transition and increased after the transition to the HS state. This is different from the hard-to-soft state transition seen in GRS 1758−258 at the end of 2001 February (Smith, Heindl, & Swank 2001). However, we have noticed that the transition in GRS 1758−258 was observed during an RXTE weekly monitoring campaign. A state transition similar to what we found in Aql X−1 could have occurred and the luminosity of the HS state could be higher than the luminosity of the LH state just before the hard-to-soft state transition.

We have found that the time lags between the occurrences of the hard-to-soft state transitions and the HS states of peak luminosities in the four outbursts are roughly 8, 11, 7, and 5 days, respectively, suggesting a positive correlation between the time lag and the peak luminosity of the outburst.

2.1. Spectral Analysis

The goal of our spectral analysis is to estimate the X-ray fluxes of these peak states as well as derive the luminosity evolution during the small flare that occurred around MJD 52100. We have extracted PCA spectra obtained in the 3–30 keV and 3–40 keV bands for the peaks of the HS and LH states, respectively. For each observation, the longest time interval with continuous coverage from all PCUs which were turned on was chosen. The standard data analysis package FTOOLS (Version 6.0.4) was used to extract the spectra, generate corresponding response matrices, and produce background files. We have applied the RXTE/PCA mission long bright source background model as well as weak source background model, since during these observations the PCA count rates reached above as well as below 40 c/s/PCU. Wherever a type I X-ray burst occurred, an interval of 100 s was excluded during the extraction of the energy spectra.

Each energy spectrum was fit using XSPEC (Version 12.2.1) with the model composed of photoelectric absorption (“wabs”), a blackbody (“bbody”), a cutoff power law (“cutoffpl”), and a Gaussian line (“gaussian”) which is fixed at 6.5 keV to account for the iron line. The
neutral hydrogen column density was fixed at the commonly-used value along the line of sight \( N_H = 3.4 \times 10^{21} \text{atoms/cm}^2 \) for Aql X–1. With model systematic errors of 1\% or less, each fit had a reduced \( \chi^2 \) less than 2, indicating acceptable agreement between the spectral shape of the simple model and the data. The best fit model parameters as well as the model fluxes in the 2–60 keV band are therefore derived.

### 2.2. Results

In Fig. 2, we plot the X-ray flux (2–60 keV) obtained in the observations of the faint outburst during which Aql X–1 started a hard-to-soft state transition around MJD 52095. The source actually rose to the flux peak of the LH state first around MJD 52085, then started a decline in the LH state of about 10 days. When the source was almost undetectable by the ASM on MJD 52095, the source started a transition to the HS state and rose in luminosity to its flux peak in the HS state around MJD 52102. An X-ray burst occurred in the HS state, suggesting that the HS state is indeed associated with a very low mass accretion rate.

There is a nearly linear relation between the HEXTE peak count rates and the ASM peak count rates. The linear Pearson correlation coefficient is 0.995. We have fit the data with a first order polynomial model, yielding \( C_{\text{HEXTE},P} = (0.65 \pm 0.17) + (2.28 \pm 0.01) \times C_{\text{ASM},P} \), where \( C_{\text{HEXTE},P} \) and \( C_{\text{ASM},P} \) are HEXTE peak rates and ASM peak rates, respectively. The relation is very tight, suggesting a prediction of an outburst peak flux is possible when the hard-to-soft state transition is observed, which was first proposed in YKF 2004. This plot is not shown, but the correlation can be inferred from the plot of the energy fluxes discussed below.

In order to investigate the relation between the energy fluxes of the hard-to-soft state transition and the peak HS state, we plot the relation between the fluxes in the energy band 2–60 keV in Fig. 3. The relation between the flux corresponding to the hard-to-soft state transition and the peak flux of the following HS state establishes a linear relation as well. The linear Pearson correlation coefficient is 0.996. The relation can be described as \( F_{\text{HS},P} = (-0.039 \pm 0.014) + (1.76 \pm 0.02) \times F_{\text{ST}} \), where \( F_{\text{HS},P} \) is the peak flux of the HS state and \( F_{\text{ST}} \) is the flux corresponding to the hard-to-soft state transition. Since the energy spectra corresponding to the LH states and the HS states are nearly identical (e.g., Yu et al. 2003), the nearly linear relation between the fluxes suggests a similar relation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state. Among the four outbursts, the largest deviation from the relation shown in Fig. 4 is about 10\%.
3. Discussion and conclusions

We have studied the RXTE observations of four outbursts of Aql X−1 in which the hard-to-soft state transitions were observed. In one of the outbursts, we have discovered a hard-to-soft state transition which occurred during a luminosity decline. We have also found that the peak luminosities of the HS states follows the X-ray luminosities of the hard-to-soft state transitions nearly linearly. The study also extends the luminosity correlation previously found by Yu, van der Klis, & Fender (2004) to lower luminosities. Using the best-fit linear relation, we can predict the luminosity at the soft X-ray peak of an outburst in Aql X−1 at the beginning of the hard-to-soft state transition to an accuracy within ∼ 10%.

The observation of the hard-to-soft state transition during a luminosity decline of a LH state is an example that the hard-to-soft state transition is not associated with the peak flux of the LH state before the state transition. In all the other outbursts of Aql X−1, as well as in the outbursts of several other transient sources such as GX 339−4, the state transitions were associated with the luminosity peaks of the LH states (Yu, Klein-wolt, Fender et al. 2003; Yu et al. 2006). Thus, it is the luminosity of the hard-to-soft state transition, instead of the peak luminosity of the LH state, that is correlated with the peak luminosity of the following HS state.

In the picture of spectral states in X-ray binaries, e.g., the model proposed by Esin et al. (1997), spectral states are determined by the mass accretion rate. A source in the LH state can only transit to the HS state when the mass accretion rate increases. Therefore the hard-to-soft state transition only occurs during a luminosity increase. The observation of a hard-to-soft state transition during a luminosity decrease in Aql X−1 contradicts with this idea, implying that other parameters in addition to the mass accretion rate determine the spectral transitions.

The nearly linear relation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state indicates that the luminosity at which the hard-to-soft state transition occurs appears determined by the peak luminosity of the following HS state, and thus by the properties of the accretion flow which powers the soft X-ray outburst. The observation challenges the interpretation that the variation in the luminosity of state transition are due to different corona size (e.g. Homan et al. 2001). Since there is a tight correlation between the luminosity of the hard-to-soft state transition and the peak luminosity of the following HS state, the cause of the variation in the luminosity of the hard-to-soft state transition is also the cause of the variation of the peak luminosity in the HS state. In the HS state, the thermal spectral component dominates, and neither a static spherical corona nor a static disk corona could power the source or collapse to form a disk flow to power the source in the HS state. Therefore, corona properties, such as corona
size or height, can not be the additional parameter determining the spectral state transitions (Yu 2006). The observation is also inconsistent with the interpretation invoking the past history of the location of the inner disk radius (Zdziaski et al. 2004). According to this interpretation, the smaller the initial inner disk radius, the faster a transient source would reach a hard-to-soft state transition and thus yield a lower transition luminosity. There would be no correlation between the luminosity of the hard-to-soft state transition and the peak luminosity of the HS state in an outburst.

The outer edge of an accretion disk in low-mass X-ray binary systems is very close to the boundary set by the Roche Lobe (e.g., Orosz et al. 1994; private communication, 2006), which suggests that disk size (i.e. the outer boundary) does not vary much. Therefore the interpretation of the state transitions invoking disk size can not be applied to interpret the variations of the luminosity of the state transition in a single source such as Aql X−1, in which the luminosity of the hard-to-soft state transition varies by an order of magnitude. The difference among the outbursts in Aql X−1 is therefore the mass in the disk and the corresponding mass distribution (i.e., surface density as a function of radius) over a more or less constant disk size. This agrees with the speculation that the mass in the disk is a parameter which determines state transitions (YFK2004). The mass and the surface density in the disk are probably correlated. The observations show a trend that the higher the peak luminosity of a soft X-ray outburst, the longer the time lag between the occurrence of the hard-to-soft state transition and the occurrence of the HS state peak. On average, the trend suggests that in a single source on different occasions, more massive disks have their maximal surface densities at larger radii. Although disk size is not the correct parameter that determines state transitions, a size parameter describing the mass distribution, e.g., the mean radius of the disk mass or the radius corresponding to the maximal surface density, may be used to describe the phenomena.

The idea that disk size affects state transitions originated from the proposed two-flow geometry, which is based on the long-term correlation between power-law indices and flux (Smith, Heindl & Swank 2001). According to this interpretation, the mass accretion rate in the disk flow is suspected to be an integration of that of a halo flow in the recent past which powers the LH state, because there is a significant difference in the viscous time scales in the disk flow and the halo flow. Although our suggestion is similar to the two-flow idea, there are fundamental differences. Our suggestion is based on the observations of individual state transitions and a correlation between the fluxes, as shown in Fig. 3. If the two-flow geometry is correct in describing the accretion flow during the state transitions, the two flows have to be related in instantaneous mass accretion rate, instead of being related in a way involving integration of mass accretion rate over time (see also YFK 2004). Less integration effect is also suggested by the time scale of the rise of the LH state and the rise of the HS state from
the start of an outburst, which only differ by a factor of two. Therefore the halo flow, if there is any, should be a sub-Keplerian flow which is very close to a Keplerian flow (see also YFK2004). It is worth noting that instead of a halo flow, we also regard an outflow as a possible alternative that powers a source in the LH state.

Our current analysis determines that it is the luminosity of the hard-to-soft state transition, instead of the peak luminosity of the LH state, that is correlated with the peak luminosity of the soft X-ray outburst. Therefore, there is only an underlying positive correlation between the instantaneous mass accretion rate at the transition and that at the luminosity peak of the HS state. The relation suggests that the X-ray radiation in the LH state is related to the optically thick disk flow further out, which, at a later time, would approach the inner most region and power a HS state. Because of the positive correlation between the luminosities, the optically thick disk in the outer region is probably the ultimate source which powers the hard spectral component originating from Comptonization of hot electrons (see also Yu 2006). Our study suggests that the disk flow may split part of its mass accretion rate to contribute to a halo flow or an outflow on its way towards the compact star. Thus, at a given time, the flux of the LH state is an integration of the contribution from the disk over a range of radii which would vary in different outbursts because of different mass distributions in the accretion disks. We speculate that the competition between the inner disk flow, which radiates soft photons and cools hot electrons, and the outer disk, which heats hot electrons, determines the spectral transition through the process of Comptonization. Assuming the mass accretion rate varies with time and radius, the hard-to-soft state transition probably occurs when the inner disk dominates as a result of the effect of the mass accretion rate at the outer disk declining faster than that of the inner disk or increasing slower than that of the inner disk. The soft-to-hard state transition occurs when the outer disk dominates as a result of the effect of the mass accretion rate through the inner disk declining faster than that of the outer disk or increasing slower than that of the outer disk. This speculation is consistent with the idea that the mass in the disk determines the state transitions since at the beginning or at the end of an outburst, most of the mass is in the outer disk. However, it is worth noting that only mass accretion rates in the disk above a certain threshold can make the way for the disk flow to enter the inner most region and establish a HS state. Aql X−1 and other sources show ‘parallel tracks’ in the color-count rate or QPO frequency-count rate plot (e.g., Munò, Remillard, & Chakrabartty 2001). It is likely that the same mechanism which causes the hard-to-soft state transition occurs at different luminosity levels also causes the so-called ‘parallel tracks’. A study of the relation between the X-ray flux, X-ray color, QPO frequencies and the mass accretion rate with these observations will be presented in a future work.
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REFERENCES


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Fig. 1.— Identification of the hard-to-soft state transitions and luminosity peaks of the four outbursts of Aql X−1 in past RXTE observations. The third one shows the hard-to-soft state transition which occurred during a luminosity decline of a LH state.
Fig. 2.— The X-ray flux (2–60 keV) evolution during the small outburst in which a hard-to-soft state transition occurred during a luminosity decline. The dashed line marks the start of the hard-to-soft state transition. Typical relative uncertainties in the X-ray fluxes are a few percent which can not be seen.
Fig. 3.— The relation between the 2–60 keV peak flux of the HS state and the 2–60 keV flux of the LH state at the start of the hard-to-soft state transition. The best-fit linear relation is plotted as a straight line.