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Effect of non-stationary accretion on spectral state transitions: An example of a persistent neutron star LMXB 4U 1636–536

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Abstract Observations of black hole and neutron star X-ray binaries show that the luminosity of the hard-to-soft state transition is usually higher than that of the soft-to-hard state transition, indicating additional parameters other than mass accretion rate are required to interpret spectral state transitions. It has been found in some individual black hole or neutron star soft X-ray transients that the luminosity corresponding to the hard-to-soft state transition is positively correlated with the peak luminosity of the following soft state. In this work, we report the discovery of the same correlation in the single persistent neutron star low mass X-ray binary (LMXB) 4U 1636–536 based on data from the All Sky Monitor (ASM) on board *RXTE*, the Gas Slit Camera (GSC) on board *MAXI* and the Burst Alert Telescope (BAT) on board *Swift*. We also found such a positive correlation holds in this persistent neutron star LMXB in a luminosity range spanning about a factor of four. Our results indicate that non-stationary accretion also plays an important role in driving X-ray spectral state transitions in persistent accreting systems with small accretion flares, which is much less dramatic compared with the bright outbursts seen in many Galactic LMXB transients.

Key words: accretion, accretion disks — X-rays: binaries — stars: neutron

1 INTRODUCTION

Black hole transients usually exhibit different spectral states during their outbursts, namely, the hard state, the soft state and the state between the two, which is called the intermediate state or the very high state (see detailed definitions in Remillard & McClintock 2006; Done et al. 2007). Similar to black hole systems, according to the source location in the X-ray color-color diagram, neutron star low mass X-ray binaries (LMXBs) also exhibit the hard state and the soft state (Hasinger & van der Klis 1989; Yu et al. 2003; Muñoz-Darias et al. 2014). In current popular theoretical models, X-ray spectral states are thought to be determined primarily by the mass accretion rate, and there is a critical threshold of the mass accretion rate – below or above which the accretion states, and therefore the spectral states, will change (e.g. Esin et al. 1997). However, X-ray monitoring observa-

tions show that the luminosity corresponding to the hard-to-soft state transition during the rising phase of outbursts in LMXB transients is usually higher than the luminosity corresponding to the soft-to-hard state transition (Miyamoto et al. 1995; Maccarone & Coppi 2003), and this is also common in neutron star soft X-ray transients (Bouchacourt et al. 1984; Yu et al. 2003; Yu & Dolence 2007). This hysteresis effect indicates that the source can stay in distinct spectral states at the same luminosity (or mass accretion rate). Moreover, the hysteresis effect is mainly driven by the large luminosity range in the hard-to-soft state transition. The luminosity corresponding to the hard-to-soft transition has been observed to vary by several times to one order of magnitude in different outbursts of single sources (Yu et al. 2004; Yu & Dolence 2007). These observations indicate that there must be other parameters than the mass accretion rate alone, which determine the source spectral states

and the state transitions. Some theories tried to explain the hysteresis effect by considering the different amount of Compton cooling or heating acting on the accretion disk corona (Meyer-Hofmeister et al. 2005) or by adjusting the viscosity parameter α (Qiao & Liu 2009), or by considering the advection dominated accretion flow with magnetically driven outflows (Cao 2016). In these stationary accretion models, however, the mass accretion rate is still the primary tuning parameter which determines the accretion or spectral state. Observations of most of the X-ray spectral state transitions in Galactic X-ray binaries, especially those in LMXB transients, do not support stationary accretion models for state transitions.

A series of investigations on spectral state transitions, based on X-ray monitoring observations, indicate that non-stationary accretion, especially that characterized by the large rate-of-change of the mass accretion rate, plays an important role in driving spectral transitions. Yu et al. (2004), Yu & Dolence (2007) and Yu et al. (2007) found a positive correlation between the hard X-ray peak flux and soft X-ray peak flux for several LMXBs (Aql X-1, XTE J1550–564, 4U 1705–44 and GX 339–4). Yu & Yan (2009) and Tang et al. (2011) performed a systematic study on about 20 and 30 persistent and transient black hole and neutron star X-ray binaries with the help of X-ray monitoring observations, respectively, which confirmed the discovery in Yu et al. (2004); Yu & Dolence (2007) and Yu et al. (2007), and found this correlation holds over a luminosity range spanning two orders of magnitude. More importantly, they also found that the rate-of-change of the X-ray luminosity around the spectral state transition is positively correlated with both the luminosity corresponding to the hard-to-soft state transition and the peak luminosity of the outbursts. Motivated by these studies, Zhang & Yu (2015) found the peak power of the episodic jet is positively correlated with both the peak luminosity of the soft state (i.e., outburst peak luminosity) and the rate-of-change of the typical X-ray luminosity around the hard state during the rising phase of outbursts in several black hole X-ray binaries in which good measurements of source distances and black hole masses are available. This series of investigations indicates that spectral state transitions, as well as accretion or jet phenomena associated with the transitions, such as episodic jets, are driven by non-stationary accretion instead of stationary accretion. One of the key elements is the important role of the rate-of-change in the mass accretion rate.

In this paper, we continue our investigation on spectral state transitions in sources showing less dramatic change in the mass accretion rates on the monitoring timescales. Our target, 4U 1636–536, is a persistent neutron star LMXB often showing small X-ray flares. It is classified as an atoll source by Hasinger & van der Klis (1989), suggesting that it usually evolves along the spectral tracks between the island state (hard) and the banana state (soft). As recorded by the *RXTE*/All Sky Monitor (ASM), *Swift*/Burst Alert Telescope (BAT) and *MAXI*/Gas Slit Camera (GSC) in the last two decades, the X-ray intensity of this source seen in X-ray monitoring observations shows flares up to a factor of ten on a timescale of about 40 days (Belloni et al. 2007) in the past few decades. It transits from the hard state to the soft state back and forth during the flares. In this work we perform a systematic study of fluxes corresponding to the hard-to-soft state transitions and their relation to the peak fluxes of the corresponding soft states.

2 OBSERVATIONS

X-ray all-sky monitors, such as *Swift*/BAT, *RXTE*/ASM and *MAXI*/GSC, have monitored 4U 1636–536 for decades on daily timescales. The monitoring light curves are publicly available. This allows us to investigate evolution of the X-ray spectral states by studying the hardness ratio between the *Swift*/BAT and *RXTE*/ASM intensity or between the *Swift*/BAT and *MAXI*/GSC intensity. We take the *Swift*/BAT data obtained in the period from 2005 February 12 (Modified Julian Day (MJD) 53413) to 2016 June 28 (MJD 57567), the *RXTE*/ASM data in the period from 2005 February 12 (MJD 53413) to 2010 April 18 (MJD 55304) and the *MAXI*/GSC data in the period from 2010 April 19 (MJD 55305) to 2016 June 28 (MJD 57567). Part of the *RXTE*/ASM and *Swift*/BAT data has been reported in Yu & Yan (2009) (from MJD 53413 to MJD 54504) and Tang et al. (2011) (from MJD 53413 to MJD 55304), however, we added more data from *MAXI*/GSC to further examine the role of non-stationary accretion in this source.

3 DATA REDUCTION

In order to show the details of the spectral state transitions during those X-ray flares, we display six typical X-ray flares with good coverage of the X-ray observations in Figure 4. Different symbols represent different flares: the blue and red data points show the light curves from
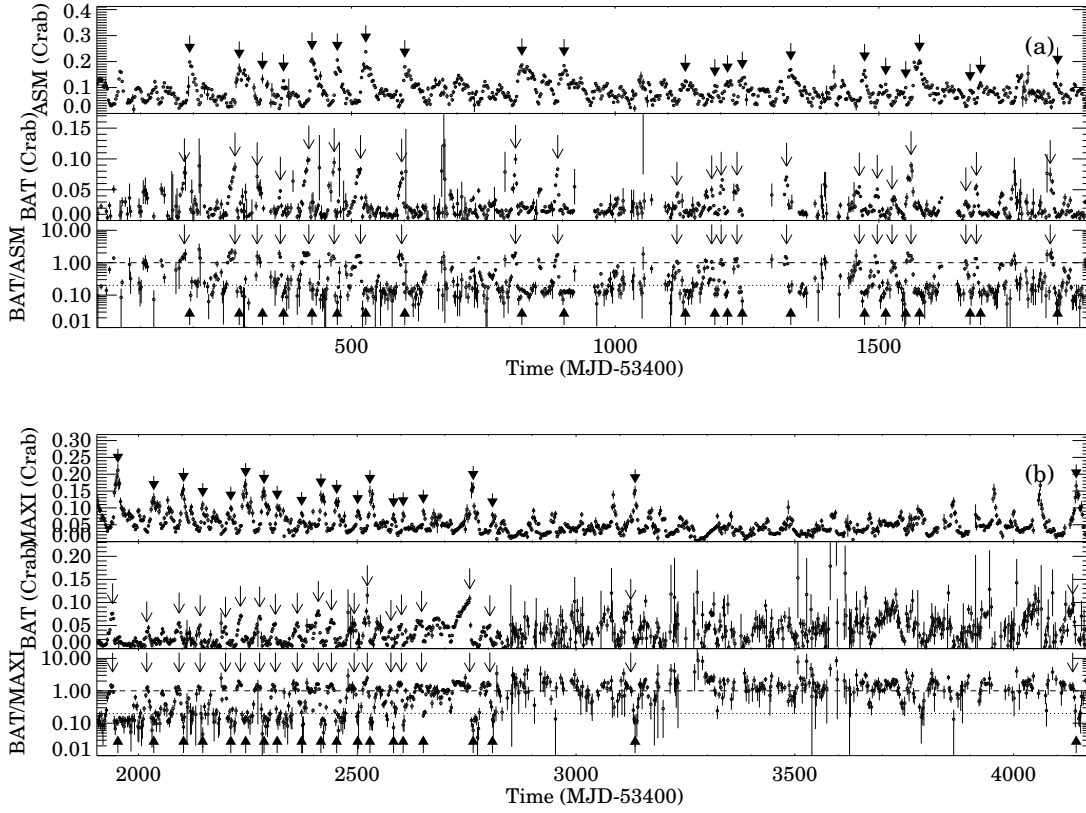
Fig. 1 X-ray monitoring observations of 4U 1636–536 with *RXTE*/ASM in 2−12 keV, *MAXI*/GSC in 2−10 keV and *Swift*/BAT in 15−50 keV. For each hard-to-soft state transition, the starting time of the transition is marked in the *Swift*/BAT light curve and the hardness ratio plot with thin arrows, and the peak flux of the following soft state is marked in the *RXTE*/ASM or *MAXI*/GSC light curve and the corresponding hardness ratio with thick arrows.

Swift/BAT and from *RXTE*/ASM or *MAXI*/GSC, respectively. The data connected with solid or dashed lines represent three brighter flares or three weaker flares, respectively. In the plot, the positive correlation can be seen. When the flux of the hard-to-soft state transition is higher in the brighter flare than that in the weaker flare, the following peak flux of the soft state is also higher in the corresponding flare, as was also demonstrated in figure 28 of Yu & Yan (2009).

All the X-ray intensity measurements have been converted into the unit of Crab. We set 1 Crab = 0.23 count s^{-1} cm^{-2} for *Swift*/BAT and 1 Crab = 75 count s^{-1} for *RXTE*/ASM. For the case of *MAXI*/GSC, the 2–10 keV intensity was estimated based on the combination of intensity of 4U 1636–536 in 2–4 keV and 4–10 keV, by using the distance 6.0±0.5 kpc (Galloway et al. 2008) and making use of measurements of the Crab X-ray luminosity in 2–10 keV according to its energy spectrum with photon index of 2.07 and normalization

of 8.26 keV^{-1} cm^{-2} s^{-1} (Kirsch et al. 2005). The difference in the estimate of fluxes in the unit of Crab brought by using different energy bands, such as 2–12 keV from *RXTE*/ASM and 2–10 keV from *MAXI*/GSC, is only about 3.7%, which is smaller than the typical error of individual daily measurements. Therefore, the measurements with different monitors can be compared consistently.

Though for the same count rate, different fluxes can be obtained from different spectra and more and more evidence shows that the spectra of neutron star LMXBs are softer than the spectra of black hole LMXBs (e.g. Weng et al. 2015; Wijnands et al. 2015), the method we applied to convert the count rate to the flux by using the Crab Nebula spectrum is still reasonable. As pointed out by Yan & Yu (2015), the difference in the flux estimated from the Crab Nebula spectrum to the flux estimated from the typical soft and hard states is about 10% and 25% in the 2–12 keV, respectively. We also com-
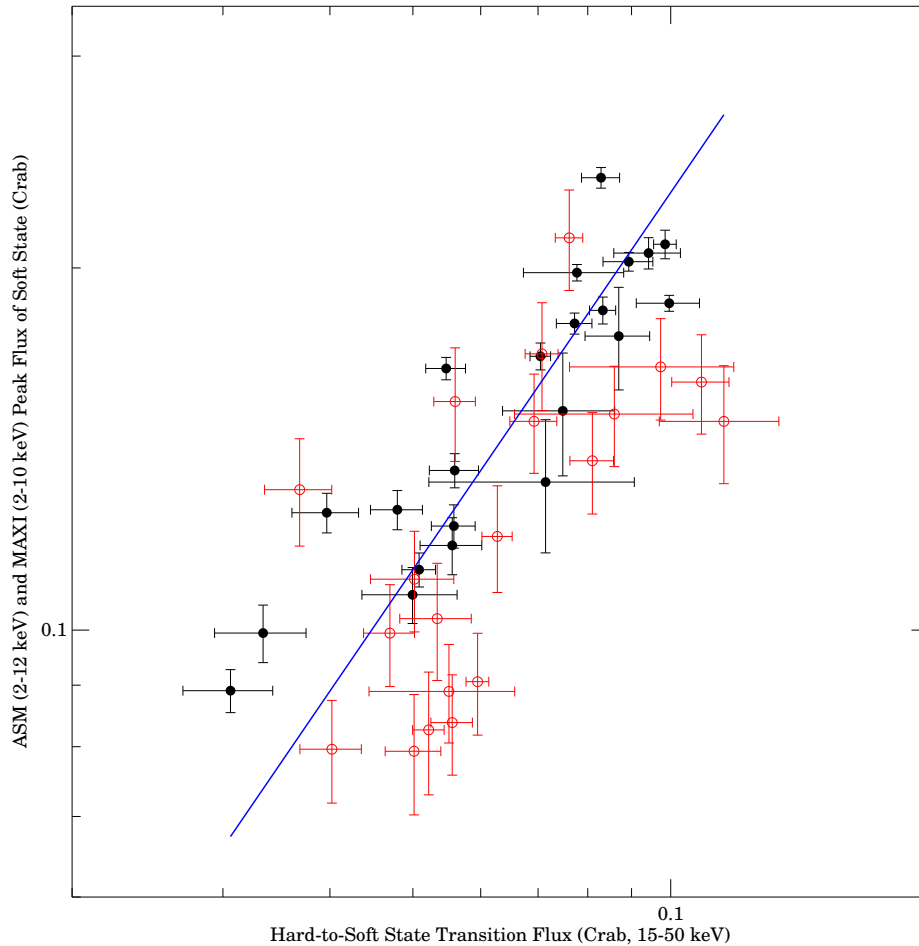
Fig. 2 The correlation between the hard-to-soft state flux and the peak flux of the soft state in 4U 1636–536. The *black filled* circles are from *RXTE*/ASM and the *red open circles* are from *MAXI*/GSC. The *blue solid line* is the linear fit result (*Color version is online*).

pared the flux estimated from the Crab Nebula spectrum and the flux estimated by fitting the quasi-simultaneous *RXTE*/PCA standard product of 4U 1636–536, and found the difference is less than 20% when the source reached the peak of the soft state. So, the uncertainty of the flux estimated from the Crab Nebula spectrum is less than about 25%.

Figure 1 shows the light curves of 4U 1636–536 observed with these all-sky monitors, which were binned to two-day time resolution to get higher signal to noise ratio. The hardness ratio was defined as the flux ratio between the *Swift*/BAT and *RXTE*/ASM or *MAXI*/GSC. We followed the same method as described in Yu & Yan (2009) and Tang et al. (2011) to search for the state transitions. According to the distribution of hardness ratios for neutron star LMXBs as shown in figure 1 of Yu &

Yan (2009), the hardness ratio thresholds for the hard state and the soft state of 4U 1636–536 are 1.0 and 0.2, respectively. The source is identified in the hard state or the soft state when the hardness ratio is above 1.0 or below 0.2, respectively. We identified the peak flux in the hard state before the hard-to-soft state transition as the transition flux based on the *Swift*/BAT light curve, and the peak flux from the *RXTE*/ASM or *MAXI*/GSC light curves as the peak flux of the following soft state. With these measurements, we will study the relation between transition flux of the hard-to-soft state and the peak flux of the soft state in the source in more details.

We notice that there is relatively good coverage using *RXTE*/PCA, with observations about every two days from March 2005 to the end of 2011. However, in order to explore the larger parameter spaces of the transi-
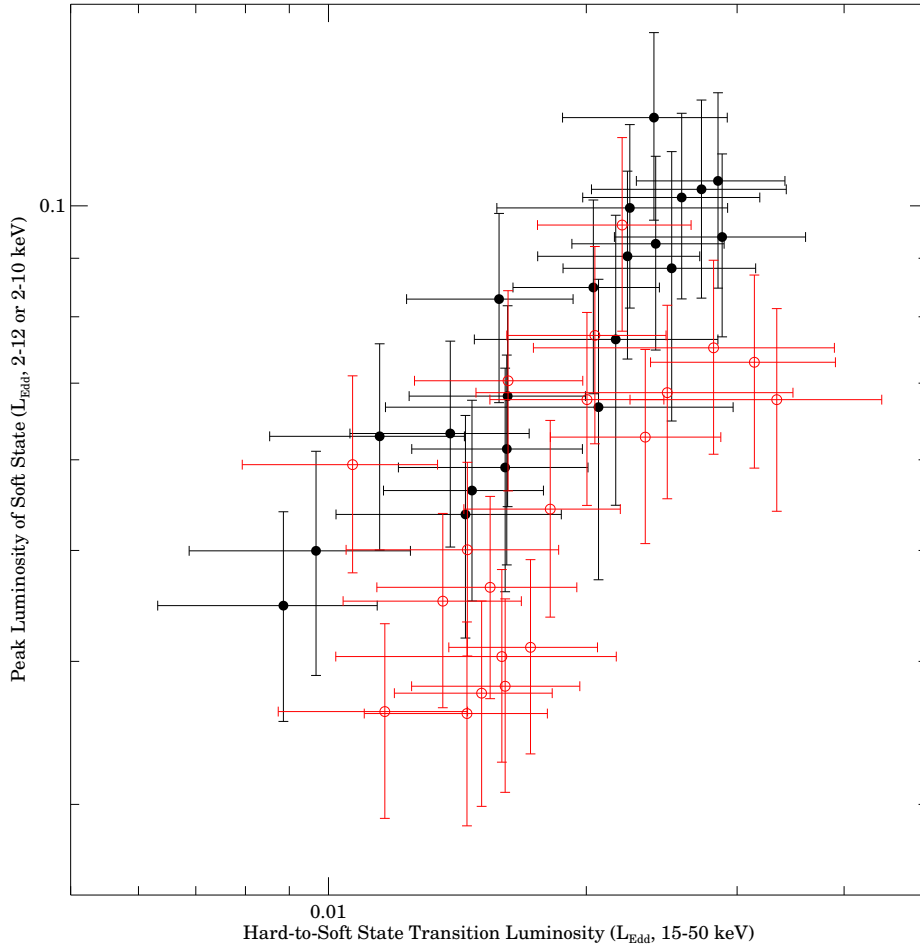
Fig. 3 The same as Fig. 2 with the unit in luminosity (*Color version is online*).

tion flux for the hard-to-soft state and the peak flux of the soft state, and to apply a consistent method as we have done in Yu & Yan (2009) and Tang et al. (2011), we use the data which spanned more than eleven years with *RXTE*/ASM, *MAXI*/GSC and *Swift*/BAT. The results of our selected data are very similar to the results of *RXTE*/PCA, which are published in Belloni et al. (2007) (see the *RXTE*/PCA light curve in fig. 1 and hardness intensity diagram in fig. 2 of that paper) and Muñoz-Darias et al. (2014) (see figs. 2 and 3 for the hardness intensity diagram and the light curve, respectively). The difference in the thresholds of the hardness ratio between ours and those in these two papers is caused by the definition of hardness ratio with different energy band.

4 RESULTS

We have identified a total of 42 hard-to-soft state transitions in 4U 1636–536 in the period between 2005 February 12 and 2016 June 28. There is a total of 22 hard-to-soft state transitions which are identified with the the *Swift*/BAT and *RXTE*/ASM data as displayed in Panel (a) of Figure 1, and a total of 20 hard-to-soft state transitions is identified with the *Swift*/BAT and *MAXI*/GSC, as shown in Panel (b) of Figure 1.

4.1 Correlation between Flux of the Hard-to-Soft State Transition and Peak Flux of the Soft State

Figure 2 shows the relation between X-ray flux corresponding to the hard-to-soft state transition in 15–50 keV and peak flux of the soft state in 2–12 keV. The data points marked in black and red in Figure 2 were obtained from the observations of *Swift*/BAT and *RXTE*/ASM, and from the observations of *Swift*/BAT and *MAXI*/GSC, respectively. The Spearman rank correlation coefficient is 0.77, with a chance probability of 2.1×10^{-9}, indicating
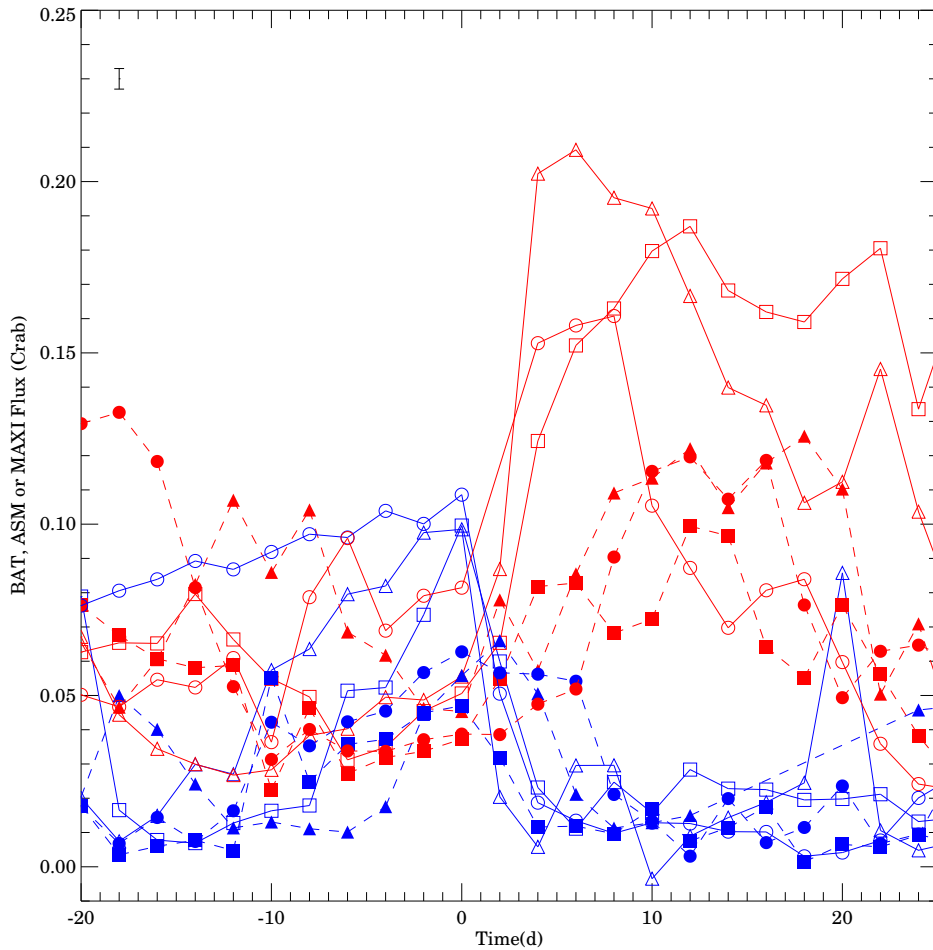
Fig. 4 Examples of the light curves for six different flares. The blue and red symbols represent the light curves of *Swift*/BAT and *RXTE*/ASM or *MAXI*/GSC, respectively. The *solid symbols* connected with *dashed lines* and *open symbols* connected with *solid lines* represent typical weaker and brighter flares, respectively. The same symbols represent the same flares. The error bar shown at the *top left corner* represents typical errors of the flux measurements. The time corresponding to the start of the hard-to-soft state transition is shifted to 0 for the light curves of *Swift*/BAT. All the light curves of *RXTE*/ASM or *MAXI*/GSC are shifted with the same time intervals corresponding to their *Swift*/BAT light curves (*Color version is online*).

that there is a strong correlation between the X-ray flux corresponding to the hard-to-soft state transition and the peak X-ray flux of the following soft state. This is direct evidence that such a correlation holds in the single source. We fit the data with a linear model of the form $\log F_{ps}=A\log F_{tr}+B$, where F_{ps} and F_{tr} represent the peak flux of the soft state and flux of the hard-to-soft state transition, respectively. We obtained $A=1.07\pm0.06$ and $B=0.44\pm0.07$. The index A is almost the same as that obtained by Yu & Yan (2009) for all the bright X-ray binaries. The correlation is not affected by uncertainties in the estimates of the source distance and neutron star mass. The X-ray fluxes were converted to luminosities by set-

ting the source distance to 6.0 ± 0.5 kpc (Galloway et al. 2008). The corresponding result is shown in Figure 3. The large error in luminosity is caused by uncertainty in source distance. The errors in transition luminosities and peak luminosities are not independent, so we do not fit the correlation, but the correlation between them should be similar to the correlation between transition flux and peak flux.

5 DISCUSSION

The luminosity corresponding to the hard-to-soft state transition can vary by about a factor of four and the peak luminosity of the soft state can vary by about a factor of

three during the flares in 4U 1636–536. Though outflows (wind or jet) will reduce the actual mass accretion rate accreted to the central compact object and the radiation efficiency may depend on the mass accretion rate for different accretion flows (Narayan et al. 1998), the variation of X-ray flux or luminosity can still roughly indicate the variation of mass accretion rate. Our results therefore indicate that the hard-to-soft state transitions can occur at different mass accretion rates spanning a large range in 4U 1636–536. This contradicts theoretical models based on stationary accretion, which predict the occurrence of hard-to-soft state transitions when the mass accretion rate exceeds a critical mass accretion rate (e.g. Esin et al. 1997).

The aforementioned series of studies on hard-to-soft spectral state transitions in black hole and neutron star X-ray binaries demonstrates that we are in need of non-stationary accretion models, which are characterized by considering rate-of-change of the mass accretion rate, for the interpretation of spectral state transitions in X-ray binaries. Several studies demonstrated that there was an obvious difference in the X-ray spectra between black hole and neutron star X-ray binaries (e.g. van der Klis 1994; Shaposhnikov & Titarchuk 2009; Farinelli & Titarchuk 2011; Weng et al. 2015; Wijnands et al. 2015; Burke et al. 2017), but non-stationary accretion plays an important role in both of these two kinds of sources (Yu & Yan 2009; Tang et al. 2011). This is because non-stationary accretion is related to the process of accretion instead of properties of the central compact object. There is no obvious difference in the hard-to-soft state transition luminosity in Eddington units between a neutron star LMXB and a black hole LMXB. For example, the luminosity in Eddington units of the hard-to-soft state transition for Aql X-1 is sometimes larger and sometimes lower than that for GX 339-4 in different outbursts (see fig. 24 in Yu & Yan 2009). Lin & Yu (2018) also concluded that the critical mass accretion rate of hard-to-soft state transition is not affected by the nature of the surface of the compact stars. According to the framework of non-stationary accretion and its effect on spectral state transitions, luminosity of the hard-to-soft transition is mainly determined by the scale of non-stationary accretion, revealing the effect of another parameter such as rate-of-change of the mass accretion rate.

As we found in 4U 1636–536, the average time interval between the occurrence of hard-to-soft state transition and the occurrence of flux peak for the soft state is about 9 days, but it can vary in a range from 2 days to 16 days in single flares when the data are binned on timescales of two days. This shortest time interval might be challenging, since if it is consistent with the viscous timescale at the inner edge of a standard thin disk approaching from a large radius to the inner most radius, the initial radius should be rather small. This challenge may be solved in future non-stationary accretion models. Unfortunately, due to the data quality, we could not measure the rate-of-change of X-ray flux in the hard state consistently among the flares, which leads to large uncertainties and strongly affects individual cases. A monitoring program with more sensitive X-ray observations in the future would help achieve such a measurement.

6 CONCLUSIONS

In this work, we report the discovery of a positive correlation between luminosity of the hard-to-soft state transition and peak luminosity of the following soft state in a single persistent neutron star X-ray binary 4U 1636–536. This is consistent with the results of previous studies on individual transient or quasi-persistent LMXBs (Yu et al. 2004; Yu & Dolence 2007; Yu et al. 2007), and all the bright black hole and neutron star X-ray binary samples (Yu & Yan 2009; Tang et al. 2011). This is the first time that such a correlation has been determined in a single persistent neutron star X-ray binary with frequent small amplitude X-ray flares. Our result indicates that there is no obvious difference in the effects of non-stationary accretion on spectral state transitions between soft X-ray outbursts in LMXB transients and small X-ray flares in persistent LMXBs except the flaring amplitude, which implies that our knowledge on regimes of non-stationary accretion is essential in understanding the properties of an accretion flow and its accretion states.

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