Super-Eddington accretion of the first Galactic Ultra-luminous X-ray pulsar Swift J0243.6+6124

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ABSTRACT
We present a detailed timing study of the pulse profile of Swift J0243.6+6124 with HXMT and Fermi/GBM data during its 2017 giant outburst. The double-peak profile at luminosity above $5 \times 10^{38}\text{erg s}^{-1}$ is found to be 0.25 phase offset from that below $1.5 \times 10^{38}\text{erg s}^{-1}$, which strongly supports for a transition from a pencil beam to a fan beam, and thus for the formation of shock dominated accretion column. During the rising stage of the high double-peak regime, the faint peak got saturated in 10-100 keV band above a luminosity of $L_t \sim 1.3 \times 10^{39}\text{erg s}^{-1}$, which is coincident with sudden spectral changes of both the main and faint peaks. They imply a sudden change of emission pattern around $L_t$. The spin-up rate ($\dot{\nu}$) is linearly correlated with luminosity ($L$) below $L_1$, consistent with the prediction of a radiation pressure dominated (RPD) disk. The $\dot{\nu}-L$ relation flattens above $L_1$, indicating a less efficient transfer of angular momentum and a change of accretion disk geometry above $L_t$. It is likely due to irradiation of the disk by the central accretion column and indicates significant radiation feedback before the inner disk radius reaching the spherization radius.

Key words: Accretion – pulsars: individual: Swift J0243.6+6124 – X-rays: binaries

1 INTRODUCTION

Recent discovery of ultra-luminous X-ray pulsars (ULXP) in nearby galaxies revealed the existence of accretion onto magnetized neutron stars with observed luminosity of 5-500 times their Eddington limit ($\sim 2 \times 10^{38}\text{erg s}^{-1}$) (e.g. Bachetti et al. 2014; Furst et al. 2016; Israel et al. 2017a, b; Carpano et al. 2018). How the accretion proceeds in such strong radiation fields and how the strong radiation affects the accretion process are unclear yet (e.g. Israel et al. 2017a; King & Lasota 2020; Mushotzky et al. 2021).

Swift J0243.6+6124 (J0243 hereafter) is a new Be-type X-ray binary discovered by Swift in October 2017 during one of the brightest outburst (Cenko et al. 2017). A pulse period around 9.8 s was detected (Kennea et al. 2017; Jenke & Wilson-Hodge 2017) with an orbital period around 27.7 days (Ge et al. 2017; Jenke et al. 2018; Doroshenko et al. 2018). The optical star was identified as a O9.5Ve star (Kouroubatsakis et al. 2017; Bikmaev et al. 2017; Reig et al. 2020). The peak flux of Swift J0243 within Swift/BAT band reached $\sim 9$ Crab. With a distance of 6.8 kpc based on Gaia data (Bailer-Jones et al. 2018), the peak luminosity of Swift J0243 is $\sim 2 \times 10^{39}\text{erg s}^{-1}$, making it the first Galactic ULXP (e.g. Tsygankov et al. 2018; Wilson-Hodge et al. 2018).

Significant evolution of temporal and spectral properties of Swift J0243 was observed during the giant outburst. Its pulse profile was double-peaked at low fluxes and changed to a single peak above a luminosity $\sim 1.5 \times 10^{38}\text{erg s}^{-1}$, and changed again to double peaks above a luminosity $\sim 5 \times 10^{38}\text{erg s}^{-1}$, as revealed by Fermi/GBM and Insight-HXMT data in high energy band (Wilson-Hodge et al. 2013; Doroshenko et al. 2020). A similar single-to-double transition around $5 \times 10^{38}\text{erg s}^{-1}$ was also found in low energy band (Tsygankov et al. 2018; Wilson-Hodge et al. 2013; Sugizaki et al. 2020). The aperiodic power spectrum density (PSD) changed with fluxes (Wilson-Hodge et al. 2013; Doroshenko et al. 2020). The spectral properties of Swift J0243 were also found to change around a luminosity of $1 - 5 \times 10^{38}\text{erg s}^{-1}$ (e.g. Wilson-Hodge et al. 2013; Sugizaki et al. 2020; Kong et al. 2020; Wang et al. 2020).

The transition of these temporal and spectral properties...
has been generally attributed to formation of an accretion column. Doroshenko et al. (2020) proposed that the transition at $\sim 5 \times 10^{38}\text{erg s}^{-1}$ could be associated with the transition of a gas-state accretion disk to a radiation pressure dominated (RPD) state. In this Letter we perform a phase-coherent pulse profile time evolution study of Swift J0243 with HXMT and GBM data to explore how an accretion column evolves with time and how it affects the accretion process.

2 OBSERVATION DATA

Insight-HXMT is a Chinese X-ray satellite launched in 2017. There are three collimated instruments sensitive to low energy (LE, 1-15 keV), medium energy (ME, 5-30 keV), and high energy (HE, 20-250 keV), with effective areas of 384, 952, and 5100 cm$^2$, respectively. For details of HXMT we refer to Zhang et al. (2020) and references therein. HXMT monitored the giant outburst of Swift J0243 almost with a daily frequency except for one week (MJD 58035-58042) at the beginning and provided a rich dataset for studies of super-Eddington accretion.

The Gamma-ray Burst Monitor (GBM, Meegan et al. 2009) on-board the Fermi spacecraft is continuously monitoring the spin histories of X-ray pulsars (Finger et al. 2007; Malacaria et al. 2020). For the date (MJD 58035-58042) without HXMT observations, we compiled the GBM pulsed profile data. Because the Fermi/GBM data is dominated by background and the constant component of GBM light curves has been subtracted, only the pulsed profile is obtained. The GBM pulsed profile is added with the Swift/BAT flux (multiplied by a constant), which is stretched by another constant. The two constants are adjusted to make the GBM profile matching that of HXMT on MJD 58043. The selected GBM bands are 12-25 keV and 25-50 keV, roughly matching the 10-30 keV and 30-50 keV bands adopted for HXMT data.

3 TEMPORAL RESULTS

To obtain phase-coherent pulse profiles, as did in Sugizaki et al. (2020), we assign a pulse phase $\phi(t)$ to the event time $t$ as $\phi(t) = \int_0^t \nu(t)dt$, where $\nu(t)$ is the pulse frequency interpolated from GBM measurements using a cubic spline function. The event arrival time $t$ is barycentric corrected using HXMT tool hxbary and is binary corrected using BinaryCor routine in Remeis ISIS.1 with the orbital parameters obtained by the GBM pulsar team.2

3.1 Evolution of the pulse profile

The pulse profiles of Swift J0243 in 1-10 keV, 10-30 keV, 30-50 keV, and 50-80 keV bands are presented in Figure 1. We first discuss the evolution of pulse profile in 10-30 keV. At the beginning of the outburst (MJD 58033-58034, the black and red lines in the first panel), the profile was dominated by two peaks. As the fluxes increased with time, the peak around 0.35 increased faster than that around 0.85. Around MJD 58037, the peak around 0.85 disappeared, a flat plateau appeared around phase 0.7, and the whole profile looked like single-peaked. This is the double-to-single transition around $1.5 \times 10^{38}\text{erg s}^{-1}$ reported in previous studies.

As the fluxes increased further, both the main peak around 0.35 and the newly emerged plateau increased together. Around MJD 58043-58044, the original peak around 0.35 was mixed with the plateau, and the mixed shape looked like a broad asymmetric bump. Meanwhile, a new, minor peak, appeared around phase 0.15. On MJD 58048 (the orange line), the signature of the original peak around 0.35 was disappeared, the peak shape was more regular, and the faint peak around phase 0.8 was also more symmetric. This is the single-to-double transition around $5 \times 10^{38}\text{erg s}^{-1}$ reported in previous studies. Note that on MJD 58048, the two peaks were located at the troughs of the initial profile on MJD 58033-59034. That is, the maximum of the emission pattern changed about 90 degree, compared with that at the beginning of the outburst.

When the fluxes took off to the peak of the outburst within MJD 58049-58064 (the right second panel), no apparent change of the peak location was observed anymore. The two peaks around 0.5 and 1.0 increased with different rates. They have similar heights on MJD 58049, but the ratio of the maximum flux of the main peak to that of the faint peak is close to 2 on MJD 58064, the peak date of the outburst.

During the fading stage of the outburst, the trend described above reversed. Around MJD 58091-58093, the shape of the main peak became bump-like again, and the faint peak became less symmetric. Around MJD 58105 (the pink line in the right third panel), the peak feature around phase 0.3 reappeared and became the peak of the profile, the previous faint peak around 1.0 disappeared, and the whole profile looked single-peaked again. After that, both the two features around 0.25 and 0.6 declined with decreasing fluxes together. Note that during this single-peak regime, the location of the reappeared main peak is a little earlier than that during the rising state. It is not certain whether this offset is real or due to some uncertainty in the phase alignment, but it will not affect the main results. As the fluxes decreased further more, a second peak around phase 0.8 reappeared around MJD 58139, and the whole profile was double-peaked again.

Therefore, one can identify two low double-peak periods and one high double-peak period (MJD 58048-58090). The high double peaks are 0.25 phase offset from the low double peaks. In between is the single-peak regime, which changed to/from the high double-peak regime around $5 \times 10^{38}\text{erg s}^{-1}$ during both the rising and fading stage. The single-peaked profile is a mix of the outburst-peak (high) feature (which is relatively lower at this time) and the initial low profile, for which only the initial main peak around phase 0.35 increased with fluxes. During this single-peak regime, the main peak of the high feature around phase 0.6 is more dominated over the faint one. The combination of features around phase 0.35 and 0.6 (which is relatively lower) made the profiles looked single-peaked.

The pulse profiles of 1-10 keV generally follow the similar evolution trend as those of 10-30 keV, but some remarkable differences can be observed. The phase position of the

1 http://www.sternwarte.uni-erlangen.de/isis
2 https://gammaray.msc.nasa.gov/gbm/science/pulsars

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Figure 1. Time evolution of the pulse profile of Swift J0243 in 1-10 keV (top left), 10-30 keV (top right), 30-50 keV (bottom left) and 50-80 keV (bottom right) during its 2017 giant outburst. The observed date of the profile since MJD 58000 are marked near the corresponding profiles. Dotted lines of 12-25 keV and 25-50 keV within MJD 58033-58043 are from GBM data while others are from HXMT data. The high double peaks are 0.25 phase offset from the low double peaks, indicating a 90 degree change of emission pattern. © 0000 RAS, MNRAS 000, 000-000
After MJD 58058, the main peak around phase 0.6 continued to already reach the maximum level on MJD 58058. The blue line in the fifth panel of Figure 1, the faint peak around 50-80 keV bands around MJD 58058. As indicated by the 3.92 Saturation of the faint peak in 10-100 keV is larger than 3 on MJD 58064. We also investigated the 0.35 peak. Such a behavior is also the more prominent the 0.35 peak is larger than 3 on MJD 58064. We also investigated the centroids of the main peak of 50-80 keV are similar during the high double-peak regime. The constant level of the pulse profile of 30-50 keV was almost unchanged. The main peak around phase 0.6 is more dominated over the faint peak compared to that in 10-30 keV. The peak position of the 30-50 keV profiles are around phase 0.6, which is about 0.05 phase later than that of the 10-30 keV profile. Meanwhile, the shape of the main peak of 30-50 keV is right-titled compared with that in 10-30 keV band.

The pulse profiles of 50-80 keV are very similar with those of 30-50 keV. During MJD 58043-58047, the main peak feature of 30-50 keV around phase 0.35 is more prominent than that of 30-50 keV. That is, the higher the energy, the more prominent the 0.35 peak. Such a behavior is also true during the decline state. During the high double-peak regime, the centroids of the main peak of 50-80 keV are similar with those of 30-50 keV, but the shapes look more right titled than those of 30-50 keV. The ratio of the maximum flux of the main peak to that of the faint peak of 50-80 keV is larger than 3 on MJD 58064. We also investigated the profiles of 50-100 keV and found they are similar to those in 50-80 keV.

3.2 Saturation of the faint peak in 10-100 keV

During the high double-peak regime, we can identify a transition of the behavior of pulse profile in 30-50 keV and 50-80 keV bands around MJD 58058. As indicated by the blue line in the fifth panel of Figure 1, the faint peak around phase 1 already reached the maximum level on MJD 58058. After MJD 58058, the main peak around phase 0.6 continued to increase until the outburst peak on MJD 58064, but the faint peak got saturated and stopped to increase any more.

Such a transition is better illustrated with the luminosity of the main and faint peak. The low-energy profile of Swift J0243 showed a significant contribution from non-pulsed emission, part of which is due to reprocessed emission as indicated by the Fe Kα emission line (Tao et al. 2013; Jaisawal et al. 2019). To reduce the effect of reprocessed and un-pulsed emission, we calculate the pulsed-only luminosity of the main and faint peak, respectively. The selected phase interval for the main peak is about 0.5, while that for the faint peak is about 0.4. As an illustration, the selected intervals on MJD 58064 are plotted in Figure 2 for 10-30 keV band. The spectra of each phase interval (also for the trough region) are extracted and fitted with a model composed of an absorbed black body and a cutoff power-law, by taking those around the profile trough as background. The pulsed luminosities of the main and faint peak in three different bands during the high double-peak regime (MJD 58048-58090) are plotted in the top two panels of Figure 3. Since the pulse profiles in 30-50 keV, 50-80 keV, and 80-100 keV are similar, we have combined these three bands into one of 30-100 keV. The unabsorbed 0.5-150 keV luminosity including un-pulsed emission is adopted as the horizontal axis. To estimate the phase-averaged luminosity, a Gaussian model of Fe Kα line is further added. We adopt a fitting energy range of 1-150 keV and extrapolate the unabsorbed model to 0.5 keV.

At the beginning of the high double-peak regime, the pulsed luminosity of the faint peak increased with the phase-averaged luminosity, and the pulsed luminosity in 1-10 keV band had a faster increasing rate than that in higher energy bands. The increasing rate in 1-10 keV band slowed down above $1 \times 10^{39}$ erg s$^{-1}$, and the faint peak got saturated in 10-30 keV and 30-100 keV bands above $1.3 \times 10^{39}$ erg s$^{-1}$, as shown by the red and green lines in the top left panel of Figure 3. During the fading stage, the pulsed luminosities of the faint peak were generally smaller than those of the rising stage and they are similar to those of the rising stage only below $7.5 \times 10^{38}$ erg s$^{-1}$. The pulsed luminosity of the main peak also had a faster increasing rate in 1-10 keV band than in other bands above $1 \times 10^{39}$ erg s$^{-1}$, but the main peak kept a similar increasing rate in all three bands above that.

The ratio of the pulsed luminosity of the faint peak to the main peak is plotted in the bottom left panel of Figure 3. The faint-to-main ratio changed hardly below $7.5 \times 10^{38}$ erg s$^{-1}$, but above that the faint-to-main ratio decreased with increasing luminosity. During the fading stage, the faint-to-main ratios were generally smaller than those of the rising stage, and they jumped back to the level of the rising stage below $7.5 \times 10^{38}$ erg s$^{-1}$. The hardness ratio of the pulsed luminosity in 10-30 keV and 1-10 keV bands (ME/LE) for the main and faint peak are plotted in the bottom right panel. The hardness ratio became softer with increasing luminosity for both the main and faint peak below $1 \times 10^{39}$ erg s$^{-1}$, but above that, it changed much less.

4 FLATTENING OF $\dot{\nu}$-L RELATION

In the standard scenario of disk accretion, the spin-up rate ($\dot{\nu}$) increases with luminosity (L). If the geometry of accretion flow changes somehow, a change of $\dot{\nu}$ – L relation will be expected. We calculate $\dot{\nu}$ by interpolating the GBM-measured spin-up rates on the correspond-
ing HXMT observation time of Swift J0243. The calculated spin-up rate against the phase-averaged luminosity is plotted in Figure 4. A flattening of $\dot{\nu} - L$ relation above $1.3 \times 10^{39}\text{erg s}^{-1}$ during the rising stage is clearly observed. The $\dot{\nu}$ within the luminosity range of $5 - 13 \times 10^{39}\text{erg s}^{-1}$ during the rising stage can be fitted with a power-law model of $\dot{\nu} = 1.15 (\pm 0.07) \times 10^{-11} L_{38}^{1.02 \pm 0.03}$ Hz s$^{-1}$, which is plotted as the blue dash line in Figure 4. In contrast, the $\dot{\nu}$ within $1.3 - 2.2 \times 10^{39}\text{erg s}^{-1}$ follows a relation of $\dot{\nu} \propto L_{38}^{0.66 \pm 0.04}$. During the fading stage, $\dot{\nu}$ are generally a little smaller than those of the rising stage above $7 \times 10^{38}\text{erg s}^{-1}$. We note that previous studies of $\dot{\nu} - L$ relation (e.g. Doroshenko et al. 2013; Zhang et al. 2019) did not distinguish the rising and fading stage and thus failed to reveal the linearity of $\dot{\nu}$-$L$ relation below $L_t$, and the flattening above $L_t$.

![Figure 3](image1.png)

**Figure 3.** The pulsed luminosity of the faint peak (top left) and the main peak (top right) within different energy bands against the phase-averaged luminosity. Bottom panels: the faint-to-main ratio and the hardness ratio. The solid line indicates the rising stage, while the dotted line for the fading stage.

![Figure 4](image2.png)

**Figure 4.** Spin-up rate vs luminosity for Swift J0243. The data points within $5 - 13 \times 10^{39}\text{erg s}^{-1}$ during the rising stage can be fitted with a power-law of $\dot{\nu} \propto L^{1.02 \pm 0.03}$ (the blue dash line), while those within $1.3 - 2.2 \times 10^{39}\text{erg s}^{-1}$ are fitted with a power-law of $\dot{\nu} \propto L^{0.66 \pm 0.04}$ (the red dot-dash line). The classical relation of $\dot{\nu} \propto L^{6/7}$ is also plotted (the green dot line). The linear relation below $1.3 \times 10^{38}\text{erg s}^{-1}$ is constant with a RPD disk. The statistical errors of both $\dot{\nu}$ and $L$ are generally better than 0.1%, but their estimation is affected by the short effective exposure ($\sim 2\text{ ks}$) for each HXMT observation. We adopt 1% uncertainty of $\dot{\nu}$ for the fitting, and the quoted errors are for 90% confidence level.

## 5 DISCUSSION AND CONCLUSION

We performed a detailed, phase-coherent pulse profile evolution study of Swift J0243 with HXMT and GBM data. We found that the high double-peak profile is 0.25 phase offset from the low double-peak profile, and the single-peaklooked profile in between is a mix of the low double-peak profile and the infant profile of the high double-peak feature. During the rising stage of the high double-peak regime, the faint peak increased with the phase-averaged luminosity below a luminosity of $L_t \sim 1.3 \times 10^{39}\text{erg s}^{-1}$, but above $L_t$, the faint peak got saturated in 10-100 keV band. The hardness ratio (ME/LE) of both the main and faint peak became softer with increasing luminosity below $L_t$, but showed much less changes with luminosity above $L_t$. During the rising stage of the high double-peak regime, the $\dot{\nu} - L$ relation follows a linear correlation below $L_t$, and flattens above $L_t$.

In the standard accretion scenario of magnetized neutron star (e.g. Gnedin & Sunyaev 1973; Davidson 1973; Basko & Sunyaev 1976), at low accretion rates, the free
falling flow is stopped by nucleon collisions at the surface of the neutron star, and X-ray radiation is emitted in a pencil beam along the magnetic pole; above a critical luminosity, the accretion flow was decelerated through a radiation shock, below which the flow slowly settles down and forms an accretion column, and X-ray photons are emitted mainly from the sidewall of the column in a fan beam (see Figure 5). Therefore, the 0.25 phase offset between the high and low double-peak profiles is a strong evidence for a transition from a low pencil beam to a high fan beam and for the existence of accretion column during the high double-peak regime. The feature of the fan beam of accretion column first appears around a luminosity of $1.5 \times 10^{38}\text{erg s}^{-1}$ and then totally dominates the profile above $5 \times 10^{38}\text{erg s}^{-1}$. So we refer the high double-peak regime (MJD 58048-58090) as after the smallest inclination angle. The different faint-to-two peaks correspond to the locations 90 degree before and of sight; while for the fan beam from accretion column, the magnetic pole has the smallest inclination angle to the line of sight.

The fitted power-law index around 1 of the $\dot{\nu} - L$ relation within $5 - 13 \times 10^{38}\text{erg s}^{-1}$ is apparently different from the value of 6/7 predicted by the standard disk accretion model (Rappaport & Joss 1977; Ghosh & Lamb 1979), but is consistent with the model prediction of a radiation pressure dominated (RPD) disk (Chashkina et al. 2017, 2019). Their calculation of a RPD disk showed that an increasing accretion rate leads to an increase in disk thickness and the pressure balance can be satisfied at a same radius for different accretion rate. As a result, the magnetosphere size of a RPD disk is almost independent on the mass accretion rate ($\dot{m}$, Chashkina et al. 2017):

$$R_{\text{in}} \approx 3.6 \times 10^7 \mu_{30}^{4/9} \text{cm}$$

(1)

where $\mu_{30}$ is the magnetic moment in units of $10^{30}\text{G cm}^3$. Then, $\dot{\nu} \propto \dot{m}$, following $2\pi \dot{\nu} = \dot{m} \sqrt{G \mathcal{M} R_{\text{in}}}$, where $I$ and $M$ are the moment of inertia and mass of the neutron star, and $G$ the gravitational constant. Such a linear dependence is consistent with the observed linear $\dot{\nu} - L$ relation below $L_1$ if the observed luminosity $L \propto \dot{m}$.

Chashkina et al. (2017) has interpreted the single-to-double profile transition of Swift J0243 around $5 \times 10^{38}\text{erg s}^{-1}$ as an indication of a possible transition of a gas-state disk to a RPD state. As mentioned before, the single-to-double profile transition marks the time when the profile was totally dominated by a fan beam and an accretion column fully came into being, and it does not necessarily mean a transition to a RPD state. Nevertheless, the linear $\dot{\nu} - L$ relation within $5 - 13 \times 10^{38}\text{erg s}^{-1}$ we found here is consistent with the existence of a RPD disk at these luminosities.

From the observed $\dot{\nu}$ around $L_1$ one can infer an inner radius of disk $R_{\text{in}} \approx 1.2 \times 10^8\text{cm}$, assuming the observed luminosity $L = \eta \dot{m} c^2$ with $\eta = 0.2$ and $I = 1.1 \times 10^{45}\text{g cm}^2$. The thickness of a RPD disk around $L_1$ is $H \approx 1 \times 10^7\text{cm}$ (Shakura & Sunyaev 1973), which could be enhanced by a factor of $\sqrt{5}$ for the disk vertical structure considered by Chashkina et al. (2017, 2019). A thickness ratio of $H/R_{\text{in}} \approx 0.2$ does correspond to the RPD regime as modeled in Chashkina et al. (2017). From Eq. 1, one can estimate a magnetic field of $B \approx 1.5 \times 10^{13}\text{G}$ for a neutron star of 1.4 $M_\odot$ with a radius of 10 km. Such a magnetic field is consistent with the observed critical luminosity for the formation of accretion column and the maximum luminosity.

\section*{Figure 5. Illustration of the pencil beam along the magnetic pole at low state with a thin disk (left) and the fan beam perpendicular to the magnetic pole (accretion column) at high state with a thick disk (right), for which the irradiation of disk by the central accretion column above a certain luminosity ($L_1$) could change the accretion disk geometry and cause a wind loss.}
of magnetized neutron stars estimated by Mushtukov et al. (2015a,b).

The flattening of the observed $\dot{v} - L$ relation indicates a less efficient transfer of angular momentum, which may be due to a loss of angular momentum and/or a change of the geometry of the accretion flow above $L_t$. If the faint peak was not saturated above $L_t$, even larger luminosity will be expected above $L_t$, and the flattening trend will be enhanced. One possible scenario of the flattening of $\dot{v} - L$ relation is through the irradiation of the disk by the central accretion column, which inflates the RPD disk, and some angular momentum is lost in a wind (Chashkina et al., 2019). If this is true, the transition luminosity of $L_t$ represents a turning-on point of significant radiation feedback of the column. Such a scenario is consistent with the possible ultrafast outflow in Swift J0243 revealed by a Chandra observation on MJD 58068 (van den Eijnden et al., 2019), when the luminosity ($\sim 1.9 \times 10^{39}$ erg s$^{-1}$) is above $L_t$. In principle, the significant radiation feedback above $L_t$ could cause a change of accretion flow and may lead to the observed saturation of the faint peak. Detailed modeling is needed to test whether the observed flattening of $\dot{v} - L$ relation and the saturation of the faint peak is really related and to reveal how the faint peak get saturated above $L_t$.

In summary, the behavior of the pulse profile from an accretion column is complex. The profiles show different shapes and phase-lags for different energy bands, and one peak could get saturated above a certain luminosity, which may be related with significant feedback of the column on the accretion flow, as indicated by a simultaneous flattening of $\dot{v} - L$ relation. These results provide a basic ground for future modeling of the formation and evolution of accretion column and for the study of super-Eddington accretion of ULXPs.

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DATA AVAILABILITY

The data underlying this article are publicly available at [http://archive.hxmt.cn](http://archive.hxmt.cn).

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