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On the relation of hard X-ray peak flux and outburst waiting time in the black hole transient GX 339-4 *(Research Note)*

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ABSTRACT

Aims. We reinvestigate the empirical relation between the hard X-ray peak flux and the outburst waiting time found previously in the black hole transient GX 339-4. We verify the relation using the observed hard X-ray peak flux of the 2007 outburst of GX 339-4, we clarify the nature of faint flares, and we estimate the lower limit to hard X-ray peak flux of the next outburst.

Methods. We analyze Swift/BAT data obtained in the past four years. Combined with the CGRO/BATSE and RXTE/HEXTE light curves, the observational data analyzed cover a period of 18 years.

Results. The observation of the 2007 outburst confirms the empirical relation discovered before, strengthening the apparent link between the mass in the accretion disk and the peak luminosity of the brightest hard state that the black hole transient can reach. We also show that faint flares with peak fluxes lower than about 0.12 crab do not affect the empirical relation. We predict that the hard X-ray peak flux of the next outburst should be greater than 0.65 crab, which will make it at least the second brightest in hard X-rays since 1991.

Key words. accretion, accretion disks – black hole physics – stars: individual: GX 339-4

1. Introduction

GX 339-4 is a black hole transient discovered more than 30 years ago. It has a mass function of 5.8 $M_\odot$, a low mass companion star and a distance of $\gtrsim$7 kpc (Markert et al. 1973; Hynes et al. 2003; Shahbaz et al. 2001; Zdziarski et al. 2004). It is among the black hole transients with the most frequent outbursts (Kong et al. 2002; Zdziarski et al. 2004). Yu et al. (2007) analyzed the long-term observations of GX 339-4 performed by the Burst and Transient Source Experiment (BATSE) on board the *Compton Gamma-Ray Observatory* (CGRO) and the *Rossi X-ray Timing Explorer* (RXTE) between May 31, 1991 and May 23, 2005. They found a nearly linear relation between the peak flux of the low/hard (LH) spectral state that occurs at the beginning of an outburst and the outburst waiting time defined based on the hard X-ray flux peaks. The empirical relation indicates a link between the brightest LH state that the source can reach and the mass stored in the accretion disk before an outburst starts.

After then, the source underwent an outburst in 2007. The 2007 outburst and any future outbursts can be used to test and refine the empirical relation. Here we show that the hard X-ray peak flux of the 2007 outburst falls right on the empirical relation obtained by Yu et al. (2007), proving that the empirical relation indeed holds. By including monitoring observations with the Swift/BAT in the past four years, we re-examine the empirical relation and predict the hard X-ray peak flux of the next bright outburst for a given waiting time. We also clarify issues related to faint flares that have been seen in the past.

2. Observation and data analysis

We analyzed observations performed with BATSE (20–160 keV) covering from May 31, 1991 to May 25, 2000, HEXTE (20–250 keV) covering from January 6, 1996 to January 2, 2006, as in Yu et al. (2007), and monitoring results of Swift/BAT that are publicly available (15–50 keV) covering from February 13, 2005 to August 31, 2009. The BATSE data were obtained in crab unit. The fluxes of the Crab were 305 counts s^{-1} and 0.228 counts s^{-1} cm^{-2} for HEXTE and BAT, respectively. These values were used to convert the source fluxes into the unit of crab. Following the previous study (Yu et al. 2007), the light curves were rebinned to a time resolution of 10 days. We note that the X-ray fluxes quoted below all correspond to 10-day averages, including those obtained in the empirical relation and the predicted fluxes.

The combined BATSE, HEXTE, and BAT light curves are shown in Fig. 1. The triangles marked with 1–8 indicate the initial hard X-ray peaks during the rising phases of the outbursts 1–8, and those with 5_e–8_e indicate the final hard X-ray peaks during the decay phases of the outbursts 5–8. Outbursts 1–7 were studied in Yu et al. (2007). Outburst 8 is the 2007 outburst that occurred after the empirical relation was obtained. The waiting time of outburst 8 is determined in the same way as in the previous study, i.e., the time separation between the peaks 7_e and 8 and the peak 7_e is the hard X-ray peak associated with the HS-to-LH transition. To show how the peaks are chosen, we also plotted the soft X-ray light curves obtained with the RXTE/ASM

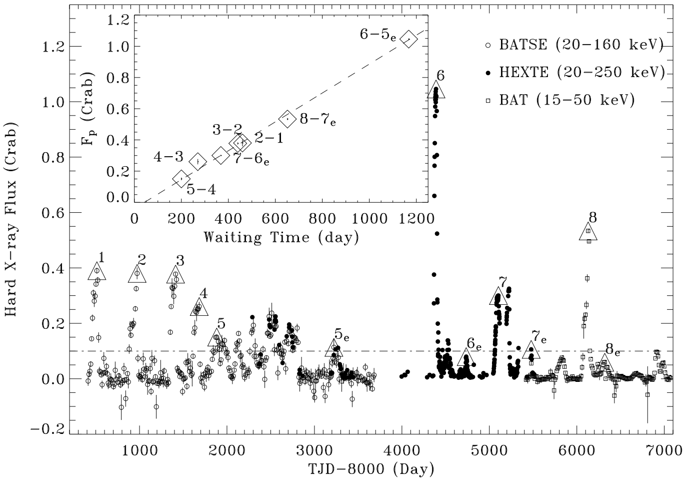

Fig. 1. The long-term hard X-ray light curves of GX 339-4 from the observations with CGRO/BATSE (empty circles), RXTE/HEXTE (filled circles) and Swift/BAT (squares). The inset panel is the relation between the LH state peak flux and the waiting time following Yu et al. (2007). The dashed-dotted line indicates the flux level of 0.1 crab, under which X-ray flares appear not to affect the empirical relation. The triangles indicate the LH state peaks used to calculate the waiting times. The dashed line in the inset panel shows the best-fitting linear model.

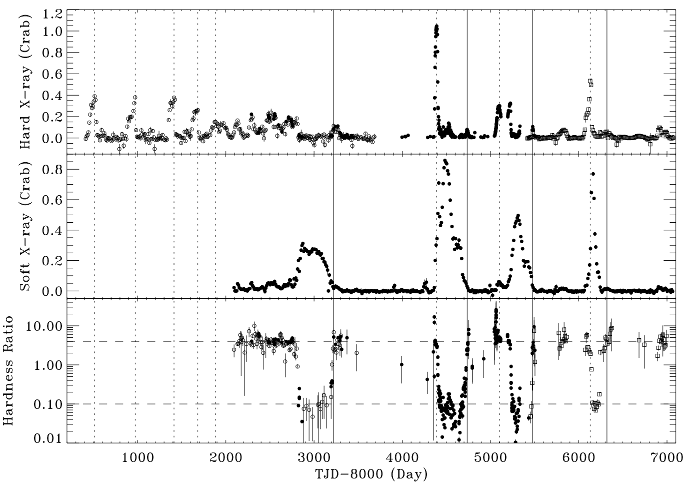

Fig. 2. *Top*: the long-term hard X-ray light curves of GX 339-4 from the observations with CGRO/BATSE (empty circles), RXTE/HEXTE (filled circles), and Swift/BAT (squares). *Middle*: the long-term soft X-ray light curve of the RXTE/ASM (2–10 keV). *Bottom*: the hardness ratios of the hard X-ray fluxes to the ASM fluxes: BATSE/ASM (empty circles), HEXTE/ASM (filled circles) and BAT/ASM (squares). The initial hard X-ray peaks and the hard X-ray peaks at the end of the HS-to-LH state transition in the outburst decays are marked with dotted lines and solid lines, respectively. The HS and LH state hardness ratio thresholds were set to be 4 and 0.1, respectively, as indicated by the dashed lines.

and the hardness ratios of the ASM to the BATSE or HEXTE or BAT fluxes in Fig. 2. This explicitly shows that the hard X-ray peaks at the end of outbursts correspond to the HS-to-LH state transitions. The initial hard X-ray peak, on the other hand, is normally the first prominent one during the initial LH state. Because of the hysteresis effect of spectral state transitions (Miyamoto et al. 1995), the source would have a very low luminosity after the HS-to-LH transition during the outburst decay. We took the hard X-ray peak corresponding to the HS-to-LH state transition such as peak 7_e, to be the end of the previous outburst, i.e., the starting time to calculate the waiting time of the following outburst (see the definition of waiting time in Yu et al. 2007).

Because of the relatively low sensitivity of BATSE, flares with 10-day averaged peak flux at or below about 0.1 crab could not be identified as individual outbursts. We therefore note that the current empirical relation is determined based on outbursts with hard X-ray peak fluxes above about 0.2 crab. For the increasingly sensitive observations of Swift/BAT, we have observed several faint flares in this source. These flares would not have been clearly identified in the BATSE 10-day averaged light curve and would not have been interpreted as single outbursts if BATSE had operated. We therefore ignored these flares, although they were clearly seen with Swift/BAT. We later discuss the faint flares.

We found that the data point of outburst 8 follows the empirical relation reported in Yu et al. (2007), as shown in the inset panel of Fig. 1. The deviation from the empirical relation is only −0.034 crab. The linear Pearson's correlation coefficient for all the 7 data points is 0.997, again indicating a nearly linear relation between the hard X-ray peak flux F_p and the waiting time T_w.

A linear fit to this relation infers that $F_p = (9.25 \pm 0.06) \times 10^{-4} T_w - (0.039 \pm 0.005)$, where F_p is in units of crab and T_w in units of days. This updated relation is almost identical to that reported in Yu et al. (2007). The intrinsic scattering of the data is 0.014 crab, which defines a ±0.014 crab bound to the linear relation. The intercept of the best-fit linear model with the waiting time axis is $T_w = 42$ days when $F_p = 0$ crab. Considering the intrinsic scattering and the model uncertainty, we obtain an intercept $T_w = 42 \pm 20$ days. This means that the hard X-ray peak of any outburst should be at least 42 ± 20 days after the end of the previous outburst, which is determined to be the hard X-ray peak corresponding to the HS-to-LH transition.

The refined empirical relation enables us to approximately estimate the hard X-ray peak flux (10-day average) of the next bright outburst in GX 339-4. The updated relation infers the peak flux of the next bright outburst to be $F_{p,n} = 9.25 \times 10^{-4}$ ($Day_{09} + T_{rise}$) + 0.44 crab, where Day_{09} is the number of days in 2009 when a future outburst starts, and T_{rise} is the rise time in units of days for the next outburst to reach its initial hard X-ray peak. The hard X-ray peak flux can be predicted almost as soon as the next outburst occurs because the rise time is a small constant compared to the waiting time. The source has remained inactive for about 750 days since the end of the 2007 outburst. This infers that the hard X-ray peak flux of the next outburst should be at least 0.65 crab (Fig. 3), which would make it the second brightest outburst since 1991, brighter than all detected outbursts except outburst 6. We again note that only for an outburst brighter than about 0.12 crab can this prediction be made based on the empirical relation. We have shown that the empirical relation holds if faint hard X-ray flares are ignored. For example, the flare of about 0.08 crab in March 2006 does not affect the peak flux of the 2007 outburst. This suggests that the flare of about 0.1 crab in March 2009 should not affect the hard X-ray peak flux of the subsequent bright outburst significantly.

The negligible effect of the faint flares on the empirical relation is also consistent with the range of values of T_w. The intersection of the best-fit linear empirical relation with the time axis indicates that the hard X-ray peak of a major, bright outburst must occur more than 42 ± 20 days after the hard X-ray peak during the decay phase of the previous outburst. However as discussed in Yu et al. (2007), the sum of the decay time of the LH state in the previous outburst and the rise time of the LH state in the next outburst is normally about 100–150 days. Therefore,

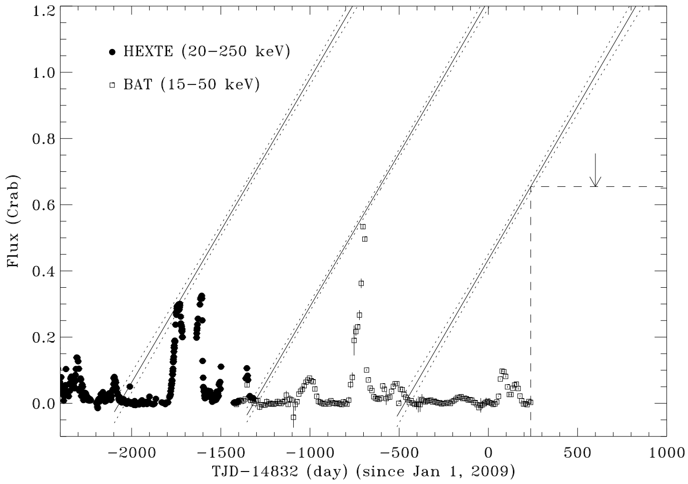

Fig. 3. Prediction of the hard X-ray peak flux for next bright outburst based on the updated empirical relation. The dashed line indicates the regime excluded for the next bright outburst. The arrow indicates the lower limit of the hard X-ray flux of the next bright outburst (in comparison to those flares fainter than 0.12 crab) is about 0.65 crab estimated on August 31, 2009 (MJD 55 074), the later afterwards the higher the lower limit will be. The "predictions" for the 2004 and 2007 outburst (outburst 7 and 8 in Fig. 1) based on the respective empirical relations derived with data before 2004 and 2007 outburst are shown as well. Data are from HEXTE (filled circles) and BAT (squares). The solid lines are the predicted values of the peak fluxes. The dotted lines show the corresponding prediction bounds at a level of 95%.

in reality the minimal T_w of bright outbursts, as defined by Yu et al. (2007), would be 100–150 days. This corresponds to F_p in the range of ∼0.04–0.12 crab, which infers a lower limit to F_p for any outburst for which the empirical relation is applicable. This might suggest that after an outburst, GX 339-4 can subsequently increase in brightness to ∼0.12 crab without returning to quiescence. Because of their low luminosities, the faint flares correspond to only a small portion of the mass in the disk. This explains consistently how when using the empirical relation without including the faint flares we can estimate the hard X-ray peak flux of a bright outburst, which is an indicator of the disk mass.

To determine the accuracy of an estimate or prediction, we also "predicted" the hard X-ray peak flux for 2004 and 2007 outbursts using the data acquired prior to the 2004 and the 2007 outburst, respectively, and then compared the "predictions" with the observations (Fig. 3). We then studied the deviations of the predicted values from the actual observed peak fluxes during the 2004 outburst and the 2007 outburst. The deviations are −0.012 crab and −0.034 crab, or 3.8% and 6.4%, respectively. Considering that the 10-day time binning should produce uncertainties, these predictions are extraordinarily precise. The prediction for the next bright outburst should be of similar accuracy. The hard X-ray peak of the next outburst should agree with the prediction in Fig. 3 with a lower limit of around 0.65 crab, which is the predicted hard X-ray peak flux of an outburst if it occurred presently (around MJD 55 074).

3. Discussion

We have analyzed hard X-ray monitoring observations of GX 339-4 with Swift/BAT in addition to CGRO/BATSE and RXTE/HEXTE observations. We have also analyzed the X-ray observations of GX 339-4 acquired in the past 18 years, following Yu et al. (2007), and re-examined the empirical relation between the hard X-ray peak flux and the outburst waiting time during bright outbursts reported by Yu et al. (2007). We have found that the hard X-ray peak flux of the 2007 outburst closely follows the empirical relation determined for observations before 2007. We checked the potential influence of faint flares on the empirical relation. The empirical relation was determined based on the observations of bright outbursts, excluding flares fainter than about 0.12 crab. The actual minimal waiting time required for an outburst to occur consistently explains that there exists a lower limit to the peak flux for the outburst studied here. A refined relation between the hard X-ray peak flux and the waiting time in the past 18 years has been obtained. Based on this relation, we have been able to estimate the hard X-ray peak flux for the next bright outburst when it begins. It has been 750 days since the end of the most recent bright outburst. Based on this, we predict that the hard X-ray peak flux should be no fainter than 0.65 crab.

During the different outbursts, the properties of the accretion flow may appear likely to be different, such that the radiation efficiencies differ for different outbursts but the actual mass accreted remains about the same. However, this is not the case. The correlation between the hard X-ray peak flux and the peak flux of the corresponding HS state is found to hold for individual black hole binaries and neutron-star low-mass X-ray binaries (Yu et al. 2004; Yu & Dolence 2007; Yu & Yan 2009). Given that the neutron star has a hard surface, the observed X-ray flux from the neutron star system should in general reflect the instantaneous mass accretion rate. Therefore, outbursts of different flux amplitudes in neutron star systems should correspond to different mass accretion rates. Because the black hole systems fall on the same correlation track as those neutron star systems, the mass accretion rates should differ when GX 339-4 reaches the hard X-ray peaks during outbursts of different amplitudes.

The empirical relation, confirmed by the BAT observations of the 2007 outburst, provides strong evidence that there is a link between the mass in the accretion disk and the brightest LH state that GX 339-4 can reach. The mechanism behind this link is not clear. But if the mass in the accretion disk is directly related to the production of the hard X-ray flux, then a major portion of the disk should be involved in generating the hard X-ray flux. Independent of accretion geometry considerations, Yu & Yan (2009) performed a comprehensive study of spectral state transitions in bright Galactic X-ray binaries. Their results confirmed the correlation between LH-to-HS transition luminosity and the peak luminosity of the following soft state shown found by previous studies (Yu et al. 2004, 2007; Yu & Dolence 2007), and provided strong evidence that: a) non-stationary accretion plays a dominant role in generating a bright LH state and b) the rate-of-increase of the mass accretion rate may be the dominant parameter determining spectral state transitions. The empirical relation between the LH-to-HS state transition luminosity and the peak luminosity of the following HS state and the empirical relation studied in this paper connect both the mass in the accretion disk (its cause and initial condition) and the peak luminosity of the hard state (its effect) with the rate-of-increase in the mass accretion rate. This may then be an indicator of the initial mass influencing the overall development of the hard state and the soft state and the transitions between the two. The empirical relation allows us to estimate the mass in the accretion disk before an outburst in the special source GX 339-4.

The phenomenon involves a storage mechanism that operated from behind. This may be relevant to phenomenon seen in solar flares, known as avalanche processes (e.g., Lu & Hamilton 1991; Wheatland 2000), for which the magnetic field plays a major role.

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