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. In this work we re-investigated 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 tested the relation using the observed hard X-ray peak flux of the 2007 outburst of GX 339-4, clarified issues about faint flares, and estimated the lower limit of hard X-ray peak flux for the next outburst.

Methods. We included Swift/BAT data obtained in the past four years. Together with the CGRO/BATSE and RXTE/HEXTE light curves, the observations used in this work cover a period of 18 years.

Results. The observation of the 2007 outburst confirms the empirical relation discovered before. This strengthens 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 smaller 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 larger than 0.65 crab, which will make it at least the second brightest in the hard X-ray 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 $\geq 7$ kpc [Markert et al. 1973; Hynes et al. 2003; Shahbaz et al. 2001; Zdziarski et al. 2004]. It is one of 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 made by the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO) and the Rossi X-ray Timing Explorer (RXTE) since May 31, 1991 until 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 the most recent monitoring observations with the Swift/BAT in the past four years, we re-examine the empirical relation and make a prediction for the hard X-ray peak flux of the next brightest outburst for a given waiting time. We also clarify issues related to faint flares that have been seen in the recent past.

2. OBSERVATION AND DATA ANALYSIS

We made use of 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 recent 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. It is worth noting that the X-ray fluxes quoted below 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 outburst 1–8, and those with $5–8$, indicate the ending hard X-ray peaks during the decay phases of the outburst 5–8. Outburst 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 $T_e$ and 8 and the peak $T_e$ is the hard X-ray peak associated with the HS-to-LH transition. In order to show how the peaks are chosen, we also plotted the soft X-ray light curves obtained with the RXTE/ASM and the hardness ratios between the ASM and the BATSE or HEXTE or BAT fluxes in Fig[2]. This explicitly shows
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.

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. Due to the hysteresis effect of spectral state transitions (Miyamoto et al. 1995), the source would have 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 $T_{c}$, as 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).

Due to 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. It is therefore worth noting that the current empirical relation is determined based on outbursts with hard X-ray peak fluxes above about 0.2 crab. In recent years with more sensitive observations of Swift/BAT, we have observed several faint flares in this source. These flares would not have been clearly seen in the BATSE 10-day averaged light curve and would not have been taken as single outbursts if BATSE had operated. Therefore we ignored these flares although they were clearly seen with Swift/BAT. We will discuss the faint flares later on.

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 gives $F_{p} = (9.25 \pm 0.06) \times 10^{-4} T_{w} - (0.039 \pm 0.005)$, where $F_{p}$ is in unit of crab and $T_{w}$ in units of days. This updated relation is almost identical to the one reported in Yu et al. (2007). The intrinsic scattering of the data is 0.014 crab, which defines a ±0.014 crab bound of the linear relation. The intercept of the best-fitting linear model on the waiting time axis is $T_{w} = 42$ days when $F_{p} = 0$ crab. Considering the intrinsic scattering and the model uncertainty, we obtained an intercept $T_{w} = 42 \pm 20$ days. This means that the hard X-ray peak of any outburst should be at least $42 \pm 20$ days after the end of the previous outburst, which is determined as 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) for the next bright outburst in GX 339-4. The updated relation gives the peak flux of the next bright outburst as $F_{p,n} = 9.25 \times 10^{-4} (D_{90} + T_{rise}) + 0.44$ crab, where $D_{90}$ is the number of days in 2009 when a future outburst starts and $T_{rise}$ is the rise time in unit of day 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 nearly a small constant compared with the waiting time. The source has remained inactive for about 750 days since the end of the 2007 outburst. This gives that the hard X-ray peak flux of the next outburst should be at least 0.65 crab (Fig. 2), making it the second brightest outburst since 1991, brighter than all the outbursts except outburst 6. Again notice that only for an outburst brighter than about 0.12 crab can such a 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 will not affect the hard X-ray peak flux of next bright outburst significantly.

The negligible effect of the faint flares on the empirical relation is also consistent with the consideration of the actual value range of $T_{w}$. The intersection of the best-fitting linear empirical relation on the time axis indicates that the hard X-ray peak of a major, bright outburst must occur more than $42 \pm 20$ days after...
This corresponds to F bursts, as defined by Yu et al. (2007), would be 100–150 days. The empirical relation derived with data before 2004 and 2007 outburst are shown as well. Data are from HEXT (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%. 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 55074), the later afterwards the higher the lower limit will be. The “predictions” for the 2004 and 2007 outburst (outburst 7 and 8 in Figure 1) based on the respective empirical relations determined with observations before 2004 and 2007 outburst are shown as well. Data are from HEXT (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 order to get an idea on how good the estimation or prediction is, we also “predict” the hard X-ray peak flux for 2004 and 2007 outbursts with the data before 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 would bring uncertainties, these predictions are extraordinarily good. The prediction made for the next bright outburst should have a similar accuracy. The hard X-ray peak of the next outburst should fall on the prediction in Fig 3 with a lower limit around 0.65 crab, which is the predicted hard X-ray peak flux of an outburst if it happened at present (around MJD 55074).

3. DISCUSSION

We included recent hard X-ray monitoring observations of GX 339-4 with Swift/BAT in addition to CGRO/BATSE and RXTE/HEXT observations. We have analyzed the X-ray observations of GX 339-4 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 found by Yu et al. (2007). We found that the hard X-ray peak flux of the 2007 outburst follows the empirical relation determined with observations before 2007 very well. We checked the potential influence of faint flares on the empirical relation. The empirical relation was determined based on the observations of bright outbursts, not including those faint flares below about 0.12 crab. The actual minimal waiting time required for an outburst to occur consistently explains that there exists a lower limit of 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 can estimate the hard X-ray peak flux for the next bright outburst as soon as it starts. 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 less than 0.65 crab.

One may think that during different outbursts the properties of the accretion flow are different, such that the radiation efficiencies differ for different outbursts while the actual mass accreted are about the same. 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 & Yuan, 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 with different flux amplitude in neutron star systems should correspond to different mass accretion rate. Because the black hole systems fall on the same correlation track as those, the mass accretion rates should be different 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 such accretion geometry considerations, Yu & Yuan (2009) have recently performed a comprehensive study of spectral state transitions in bright Galactic X-ray binaries. The results have confirmed the correlation between LH-to-HS transition luminosity and the peak luminosity of the following soft state shown in previous studies (Yu et al., 2004; 2007; Yu & Dolence, 2007), and provided strong evidence for 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 can 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 the mass in the accretion disk (the cause and initial condition) and the peak luminosity of the hard state (the result) to the rate-of-increase of the mass accretion rate. This then could be the indicator of the initial mass which influences the overall development of the hard state and the soft state and the transi-
tions 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 reminds us of a storage mechanism that works behind. This may be relevant to the phenomenon seen in solar flares, known as avalanche processes (e.g., Lu & Hamilton [1991], Wheatland [2000], of which the magnetic field plays the major role.

Acknowledgements. We would like to thank the CGRO/BATSE group at NASA Marshall Space Flight Center and the RXTE and the Swift Guest Observer Facilities at NASA Goddard Space Flight Center for providing monitoring results. WY would like to thank Robert Fender for stimulating discussions and hospitality and encouragement which speeded up this work. WY also thank Tomaso Belloni for a careful check of the BAT flux for the 2007 outburst of GX 339-4. This work was supported in part by the National Natural Science Foundation of China (10773023, 10833002), the One Hundred Talents project of the Chinese Academy of Sciences, the Shanghai Pujiang Program (08PJ141111), the National Basic Research Program of China (973 project 2009CB824800), and the starting funds at the Shanghai Astronomical Observatory. The study has made use of data obtained through the High Energy Astrophysics ScienceArchive Research Center Online Service, provided by the NASA/Goddard Space Flight Center.

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