Discovery of the black hole candidate Swift J1539.2-6227

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December 17, 2009

ABSTRACT

We report on the discovery by the Swift Gamma-Ray Burst Explorer of the black hole candidate Swift J1539.2-6227, during normal observations with the Swift Burst Alert Telescope. An extended observing campaign with the Rossi X-Ray Timing Explorer and the Swift XRT provided coverage over 175 days, giving us a rare opportunity to track the evolution of spectral parameters with fine temporal resolution through a series of spectral states. During the initial low/hard state, the peaks of the hard (15-50 keV) X-rays preceded the peaks of the soft (1.5-12 keV) X-rays by several days. Also during this phase, quasi-periodic oscillations were observed with frequencies between 0.1 and 4 Hz. The source later entered a high/soft state which showed a gradual decline to quiescence marked by several episodes of spectral hardening. We report on the observations that led to the discovery of the source, discuss how the spectrum evolved over the duration of the outburst, and provide arguments supporting the identification of the source as a black hole candidate.

Subject headings: gamma rays: bursts

1. Introduction

The galactic source Swift J1539.2-6227 was discovered with the *Swift*/BAT Hard X-ray Transient Monitor and on 2008 November 24 (MJD 54794). RXTE observations began two

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days later and continued for a total of 159 observations over the next 176 days. Early timing analysis showed the presence of low-frequency QPOs and the absence of pulsations. This suggested that the source was likely a black hole binary in outburst. Further observations showed evidence for the state transitions that mark black hole systems. Optical spectroscopy and the faintness of the quiescent source suggest that the companion is a low-mass star. Therefore we conclude that Swift J1539.2-6227 is LMXB BH candidate system.

2. Summary of Results

- Swift J1539.2-6227 is a recently discovered LMXB BH system.
- We have collected a long set (160 observations) of RXTE data from which we have performed spectral analysis and preliminary timing analysis.
- We observe the transition from a Low-Hard state to either a High-Soft or Intermediate state and then the start of a transition back to the LH state.
- We see that the hard X-ray peak precedes that soft X-ray peak by ≈ 8.5 days and that there is strong correlation between the shifted peak light curves.

3. Observations

The discovery of Swift J1539.2-6227 was announced in the Astronomer's Telegram #1855 (Krimm et al. 2008) and initiated a long series of observations with the *Rossi X-ray Timing Explorer*. RXTE Cycle 12 ToO observations began on 2008 Nov 26 and continued through 2009 March 3 and a further set of Cycle 13 observations continued until 2009 May 21 with an additional single observation on 2009 July 26. At the time of the discovery, the source was too near the sun for *Swift* narrow-field instrument observations. The first *Swift*/XRT observation was carried on 2008 December 25 (MJD 54825). A total of six *Swift* pointed observations were made at the times indicated by the arrows in the top panel of Figure 1.

In observations with the *Swift* /UVOT), a bright source was found in a 3906-s co-added uvw2 exposure at the location:

$$RA(J2000) = 15:39:11.963 \quad (234.79985^\circ)$$
$$Dec(J2000) = -62:28:02.30 \quad (-62.46731^\circ)$$
$$G_{lat} = 321.018595^\circ \quad G_{lon} = -5.642750^\circ$$

with a positional uncertainty of 0.5″ (90% confidence). There are no known sources coincident with this position found in the USNO-B1, USNO-A2 or 2MASS catalogs. At the time of the observation the companion magnitude was 18.07 ± 0.03 (uvw2) and 17.96 ± 0.04 (uvm2).

Torres et al. (2009) report optical spectroscopy from Swift J1539.2-6227. A single 750-sec spectrum of the optical counterpart to the X-ray transient was acquired with the MagE echellette spectrograph on the Magellan-Clay telescope at Las Campanas Observatory on 2009 Feb 23 09:28 UT. Besides a blue continuum, no Balmer lines (in emission/absorption) were detected, nor was there evidence for HeII 4686 Åor Bowen blend emission. The non-detection of emission lines found often in optical spectra of X-ray transients is rare but not unprecedented. Given the lack of any emission features in the outburst spectrum combined with the faintness of the source in quiescence suggests a low-mass main sequence or degenerate donor star companion to the compact accretor.

We do not have radio or other known optical observations of this source.

4. Data Analyis

The light curves for four instruments are shown in Figure 1. The BAT and ASM light curves were taken from the public web pages. The PCA and HEXTE light curves were based on the current work. The PCA rate peaked at 472 ± 0.3 ct/s on MJD 54815, corresponding to a flux of $4.8 \times 10^{-9}\ erg\ cm^{-2}\ s^{-1}$ in the 3-25 keV band, and declined by nearly three orders of magnitude by MJD 54970. The longer term BAT and ASM light curves show no detectable emission before MJD 54790 or after MJD 55050.

We were able to fit the combined PCA and HEXTE data for 140 of the 160 observations. The fit model used was (using xspec12 models) constant * (wabs * (diskbb + kdblur * (cutoffpl + gaussian))). After making several trial fits, we decided to freeze several of the fit parameters, as listed in Table 1. The value for n_H was taken from the average of the fits to the joint PCA/HEXTE/XRT spectra. The accretion disk radii were chosen as values typical for such systems. The gaussian line width was set to zero and the line smoothed by the relativistic effects of the kdblur model. During all phases of the outburst, we see a feature that we interpret as an iron line at 6.58 ± 0.29. The fraction of the total flux in the line component is $< 5\%$.

The emissivity index in the *kdblur* model was difficult to fit well. The spectra in which it was constrained show a fairly constant cluster at around -2.6. This is a physically reasonable value within the range suggested by Laor (1991). We had even greater difficulty fitting the disk inclination angle. We have no outside knowledge of what the inclination is; however, we do not expect it to change. The spectral fits show a large amount of scatter in the inclination, but where is it moderately constrained, we find an average of $53° \pm 7°$. The other free parameters from the fits are discussed below.

We also performed joint XRT/PCA/HEXTE fits for the six epochs with XRT observations. Results were consistent with the fits described above. Using the XRT we were also able to fit the absorption, $n_H = 0.4 \times 10^{22} cm^{-2}$. Example joint spectral fits (for MJD 54825-26) are shown in Figure 5.

5. Correlation between Hard and Soft X-ray Peaks

Figure 1 shows that the flux peaked in the BAT and HEXTE energy ranges before it peaked in the PCA and ASM. It is found (Top panel of Figure 3) that if the early part of the BAT light curve is shifted 8.5 days later in time, it matches quite well with the first two peaks in the PCA light curve. After the first peak, the BAT and PCA light curves show a close alignment. Note that the intensity of later peaks relative to the first peak is lower in the BAT than in the PCA. The HEXTE light curve (not shown) tracks the BAT light curve quite closely. We also plot the BAT count rate (shifted by 8.5 days) against the PCA rate in the bottom panel of Figure 3. We see a good correlation, especially for the first peak, where the Spearman rank correlation coefficient (ρ) is 0.88. For the combined first and second peaks, $\rho = 0.65$.

This correlation between the hard X-ray peak during the Low-Hard State and the first X-ray peak in the High-Soft State has been seen before. Brocksopp et al. (2006) reported a similar result for GRO J1655-40 and found a shift of 7 days. Smith, Heindl & Swank (2002) see delays clustered around 11 and 25.5 days for various spectral parameters for 1E 1740.7-2942, another LMXB. Yu, Van der Klis & Fender (2004) discuss this effect for a number of low-mass X-ray binary transients, both black hole and neutron star systems. Their conclusion is that the early outburst accretion is composed of two related flows: first, a non-disk flow from the outer disk generates the hard X-ray flux, then an optically thick disk flow, which propagates inward on a viscous timescale, generates the lower energy flux a few days later. They also infer that the two flows supply proportional amounts of matter. Our results from the initial Swift J1539.2-6227 outburst peak support these conclusions.

6. State Transitions

Swift J1539.2-6227 appears to go through at least one and likely two state transitions during its outburst. We note a transition from the Low-Hard (LH) state to the High-Soft (HS) state at approximately MJD 54805 and what appears to be a transition back to a LH state beginning around MJD 54940.

Initial Low-Hard and Transition States The source is first seen in what is probably a short-lived outburst in the Low-Hard State. This corresponds to the highest peak in both BAT (15-50 keV) and HEXTE (16-100 keV). The hardness ratio HR (5-12 keV)/(3-5 keV) starts near 1.5, which is the value McClintock & Remillard (2006) give as characteristic of the LH state. By the transition, HR has dropped to 0.7.

The photon power-law index also shows a trend from hard (1.1) to soft (2.2) during this period. Furthermore, it is only during this time that a power-law cutoff is clearly required in the spectral fits. The cut-off energy is quite steady at an average of 38.1 ± 1.7 keV up through MJD 54804, after which point the fits show no cut-off below 500 keV. The disk temperature shows a decline from 1.2 keV to 0.9 keV.

Motta, Belloni & Homan (2009) discuss the evolution of the spectral fits through the hard to soft transition. For the black hole candidate GX 339-4, they show a full transition from LH to HS state over about eight days, with the hardness ratio falling and power-law index rising steadily during the transition. They also show a steady drop in the cut-off energy preceding the transition and a sharp rise during the transition. Just before the transition, the cut-off energy in GX 339-4 is just above 50 keV, similar to what we see for Swift J1539.2-6227. By contrast, our results show the transition without the preceding flat period, suggesting that the LH state of the outburst was *very* short (≈ 2) days, since the first strong detection in the BAT preceded the first PCA observations by only two days. By contrast, the initial rise in the BAT count rate for GX 339-4 preceded the hard-soft transition by ≈ 80 days.

We also derive a hardness-intensity diagram (HID) similar to those in Fender, Belloni & Gallo (2004) and Motta, Belloni & Homan (2009). The letters on the plot correspond to significant turning points in the trace. Note that we do not see the long vertical segment which would precede point A and correspond to the canonical LH state. Therefore, this diagram suggests that the transition in Swift J1539.2-6227 begins at point A and is largely complete by point B and that we do not observe (other than in the BAT) the rise to the peak of the LH state.

High-Soft or Intermediate States. After MJD 54805, Swift J1539.2-6227 moves into what is either a HS state or some intermediate state. The power-law index remains quite steady for about 135 days at around 2.2, with no sign of the sharp softening which would signal a Very High (VH) state. The disk temperature falls fairly gradually from 0.9 keV at the start of the intermediate state to about 0.5 keV at the end. There are rises in temperature at close to the same times as increases in hardness. With some excursions, this is a period of steady decline in flux in all four instruments. In the HID, we see the usual back and forth in phase space as the hardness varies across a range of intermediate states, while the flux gradually declines.

Transition back to the Low-Hard State. After roughly MJD 54940, there is a sharp drop in the power-law index along with an increase in disk temperature. The hardness ratio also starts to rise at this time and there is a peak in both the PCA and BAT light curves at around MJD 54950. There is some indication that there is again a spectral energy cut-off after MJD 54940, but the statistics are poor on this fit parameter. The change in PL index and HR, together with the trace H-I in the HID suggest that the source is making a transition back to the LH state. The increase in disk temperature, while significant, is surprising since it is more common for the temperature to fall at such a transition.

By the time the PCA observations ended, the key parameters (hardness ratio and spectral index) had not yet settled out. Again, comparing to Motta, Belloni & Homan (2009) shows that our observations end during a possible transition back to the HS, but do not reach the vertical segment in the HID that would indicate a full return to the LH state. Therefore, we conclude that we observe the transition back to a LH state, but not the full return to this state.

We were unable to fit the spectra of the final observation at MJD 55038, but we note that the PCA and HEXTE fluxes are nearly the same at this late point as they were before. This suggests the possibility that there is some contamination from the galactic ridge. However, the BAT light curve also is approximately flat over this period, suggesting that the source itself may still be active.

7. QPOs

Preliminary analysis shows a QPO for the first five PCA observations (MJD 54796 – 54803) with a central frequency increasing from 0.15 Hz to 4 Hz. The PL spectral index also softens over this period from 1.7 to 2.4. These QPOs occur along the path A-B in Figure 4. There is no indication of a QPO below 5 Hz from MJD 54804 through 54902. Further timing analysis is ongoing.

8. Summary and Discussion

The recently discovered source Swift J1539.2-6227 displays many of the classic features of a black hole transient in outburst. It also shows a clear and correlated lag of $\approx$ 8.5 days between the hard X-ray and soft X-ray peaks bracketing the LH to HS state transition. We do not see a spectral indication of a VH state in the outburst progression.

9. Future Work

- Redo the spectral fits to (a) allow the inner disk radius to be a free parameter, (b) determine the equivalent width of the line feature, (c) attempt to better restrict the emissivity index parameter.
- Complete the joint XRT/PCA/HEXTE fits and compare with PCA/HEXTE results.
- Perform timing analysis on the full data set to determine whether there are weak or higher frequency QPO features at later times and to search for second harmonics. Calculate Q factors and amplitudes of the timing features.
- Analyze the UVOT data for the remaining five XRT observations.
- Perform delay analysis similar to that of Smith, Heindl & Swank (2002) for the full outburst light curves.

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This preprint was prepared with the AAS LaTeX macros v5.2.

Table 1. Average spectral fits for Swift J1539.2-6227

Model	Parameter	Units	Mean	Spectra used[a]	Notes
wabs	n_H	atoms/cm^2	4.0×10^{21}	–	frozen
kdblur	Emissivity index	–	2.6 ± 0.7	45	
kdblur	Inclination	degrees	53 ± 7	66	
kdblur	Inner radius	(GM/c^2)	4.5	–	frozen
kdblur	Outer radius	(GM/c^2)	100.0	–	frozen
cutoffpl	High energy cut-off	keV	38.1 ± 1.7	5	before MJD 54804
gaussian	Line energy	keV	6.58 ± 0.29	134	
gaussian	Line width	keV	0.0	–	frozen

[a]This column gives the number of spectra (out of 140 total) in which the particular parameter was well constrained.

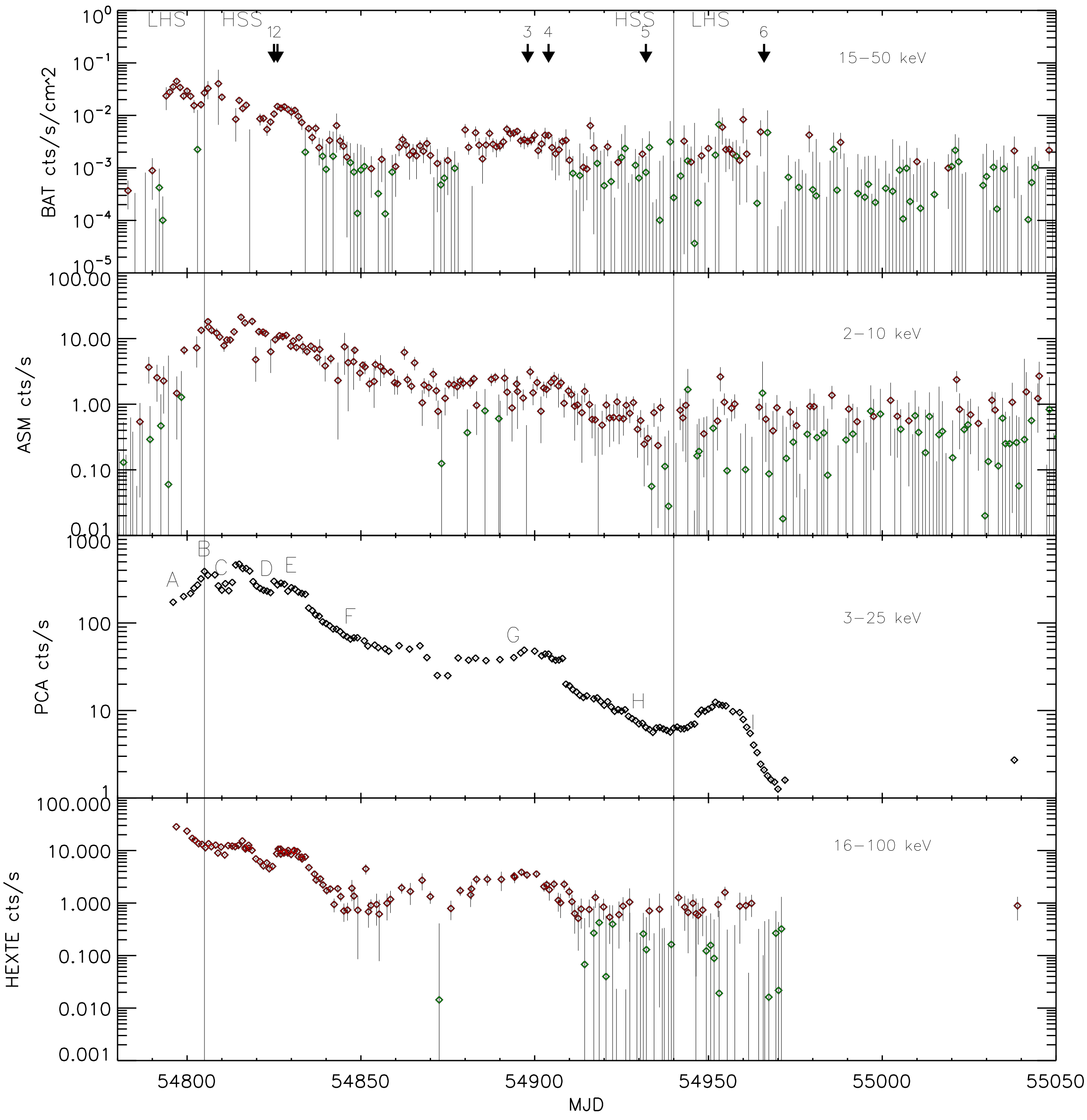

Fig. 1.— Light curves for Swift J1539.2-6627 for the four instruments, *Swift/BAT*, *RXTE/ASM*, *RXTE/PCA* and *RXTE/HEXTE*. On the BAT plot, the times of the Swift/XRT observations are shown. The solid vertical line in this and subsequent plots represents the proposed transition from the initial low-hard state to the high-soft state. On the BAT, ASM and HEXTE light curves red points are detections (error bars do not include zero) and green are upper limits. Note that the final PCA/HEXTE point corresponds to a detection in both BAT and the ASM, which suggests that the flux has remained constant during this interval. The letters in the PCA panel correspond to the turning points in the hardness-intensity plot in Figure 4. The vertical lines represent the proposed transitions from the Low-Hard State (LHS) to the High-Soft State (HSS) and back.

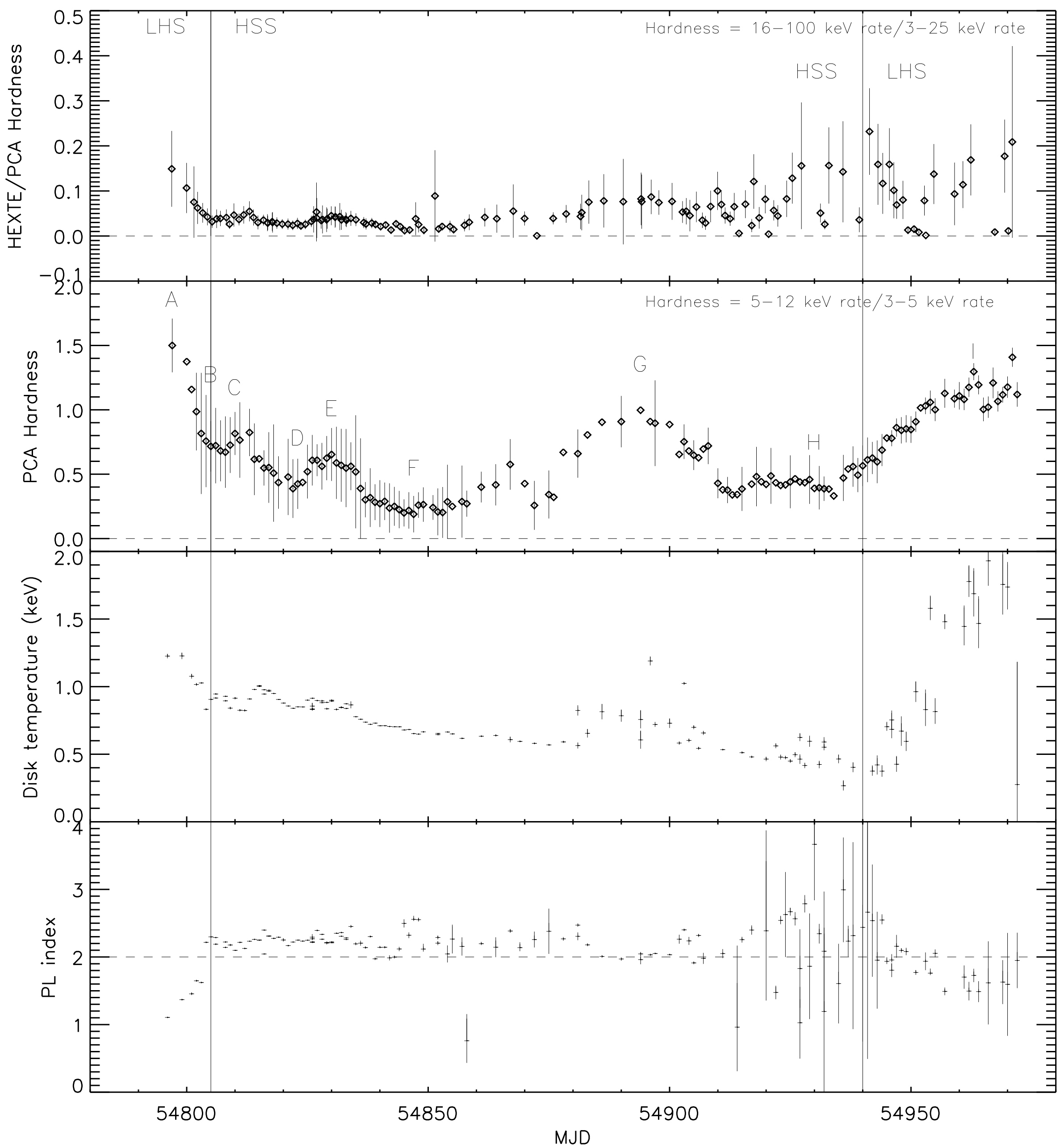

Fig. 2.— Hardness ratios and fit parameters. The top panel relates HEXTE rates to PCA rates in the energy bands indicated. The second panel shows the PCA hardness ratio. The letters correspond to the turning points in the hardness-intensity plot in Figure 4. The third panel shows the disk temperature for a black body model. The temperature shows a mostly steady decline from roughtly 1.0 keV to 0.4 keV until about MJD 54950, after which it rises sharply to nearly 2.0 keV. The bottom plot shows the power-law index, which is hard early in the outburst, then remains steady at near 2.2 before hardening again near MJD 54955, a few days after the temperature starts to rise. The vertical lines represent the proposed transitions from the Low-Hard State (LHS) to the High-Soft State (HSS) and back. The horizontal line in the bottom panel is to guide the eye.

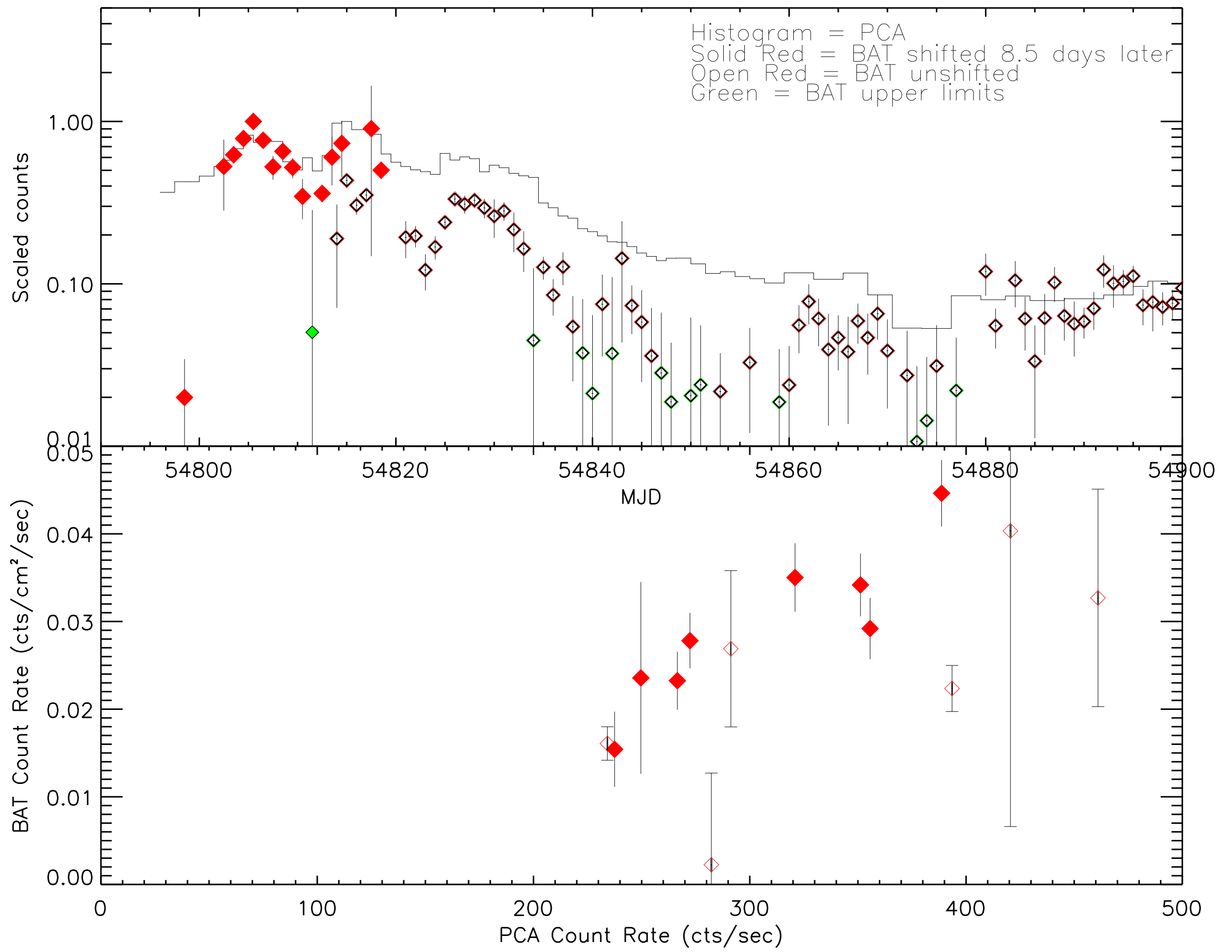

Fig. 3.— Top Panel: This figure shows the correspondence in features between the PCA (3-25 keV) light curve (histogram) and the BAT light curve when it is shifted forward in time by 8.5 days. The first two peaks and the dip between them match quite well as does the shoulder at around MJD 54835. Bottom Panel: Cross plot between BAT (shifted forward by 8.5 days) and PCA. The solid points are from the first peak (up through MJD 54810 and the open points are from the second peak.

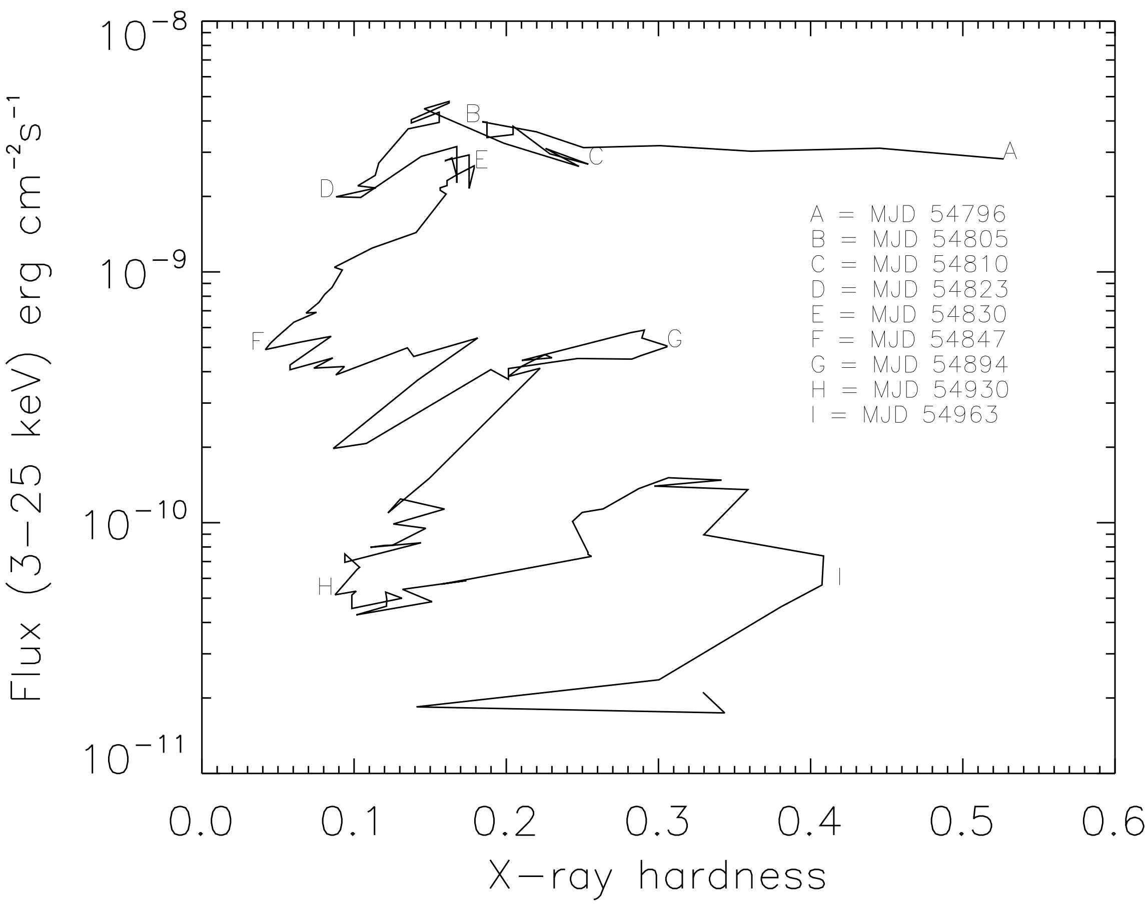

Fig. 4.— Hardness-intensity diagram for Swift J1539.2-6227 showing the flux in the 3-25 keV band versus the X-ray color (9-25 keV/3-9 keV). The letters represent major changes in direction of the trace.

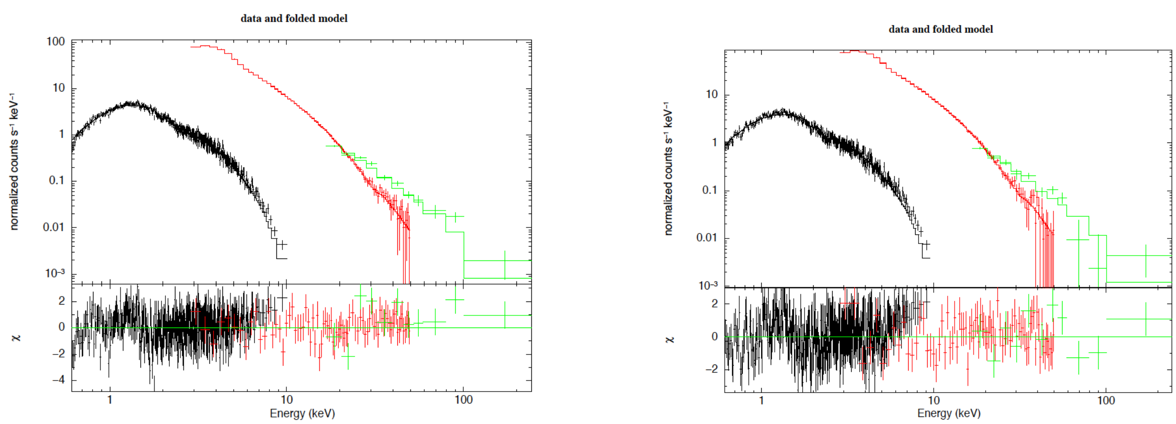

Fig. 5.— Sample joint spectral fits from XRT (black), PCA (red) and HEXTE (green).