Orbital period of Swift J1816.7–1613 revealed by the Swift Burst Alert Telescope

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Accepted 2014 September 5. Received 2014 September 5; in original form 2014 July 18

ABSTRACT

We have analysed the Swift data relevant to the high-mass X-ray binary Swift J1816.7–1613. The timing analysis of the Burst Alert Telescope survey data unveiled a modulation at a period of \( P_0 = 118.5 \pm 0.8 \) d, which we interpret as the orbital period of the X-ray binary system. The modulation is the result of a sequence of bright flares, lasting \( \sim 30 \) d, separated by long quiescence intervals. This behaviour is suggestive of a Be binary system, where periodic or quasi-periodic outbursts are the consequence of an enhancement of the accretion flow from the companion star at the periastron passage. The position of Swift J1816.7–1613 on the Corbet diagram strengthens this hypothesis. The broad-band 0.2–150 keV spectrum is well modelled with a strongly absorbed power law with a flat photon index \( \Gamma \sim 0.2 \) and a cut-off at \( \sim 10 \) keV.

Key words: surveys – X-rays: binaries – X-rays: individual: Swift J1816.7–1613.

1 INTRODUCTION

A significant fraction of cosmic X-ray sources are transient systems, with long periods of quiescence interrupted by brief intervals of intense emission. X-ray detectors with a large field of view play a fundamental role in the detection and study of these systems. Within this class of telescope, the Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the Swift satellite (Gehrels et al. 2004) is proving to be a valuable instrument in fulfilling this aim. Since 2004 November, the BAT has been performing a continuous monitoring of the hard X-ray sky. While it is hunting for gamma-ray bursts, it also records the flux variability of known X-ray sources and discovers many new X-ray transients (Krimm et al. 2013).

In this letter, we analyse the soft and hard X-ray data collected by Swift on Swift J1816.7–1613, a Galactic X-ray transient unveiled by the BAT (Krimm et al. 2008). The source was first detected at \( \sim 24 \) mCrab in the 15–50 keV band on 2008 March 24 and its intensity rose to \( \sim 35 \) mCrab on March 29. The source was also revealed by the BAT during two other less-intense outbursts, one from 2009 July 21 to 2009 August 10 and the other from 2011 June 18 to 2011 July 8. During both episodes, the outburst peaked at \( \sim 30 \) mCrab in the 15–50 keV band (Krimm et al. 2013). From the examination of the long-term BAT light curve, and following a more recent outburst in 2014 June, Corbet & Krimm (2014) suggest an orbital periodicity of \( \sim 151 \) d and argue that the sporadic appearance of the outbursts along the light curve is consistent with the source being a Be/neutron star binary system. The X-ray transient was detected serendipitously in a Chandra Advanced CCD Imaging Spectrometer (ACIS) observation performed on 2007 February 11 (Halpern & Gotthelf 2008). The position of the X-ray source measured by Chandra is RA = 18°16′42.66, Dec. = −16°13′23.4′′ (J2000). The energy spectrum was modelled by a power law of photon index \( \Gamma = 1.2 \), a column density \( N_H = 12 \times 10^{22} \) cm\(^{-2} \), and a 2–10 keV flux of \( 4 \times 10^{-12} \) erg cm\(^{-2} \) s\(^{-1} \). A timing analysis of the Chandra event arrival times has also revealed that the source is a high-mass X-ray pulsar with a spin period of \( \sim 143 \) s (Halpern & Gotthelf 2008). The analysis of two follow-up observations performed with the Rossi X-Ray Timing Explorer (RXTE) Proportional Counter Array (PCA) on 2008 March 29 and April 7 confirmed the pulse period and revealed weak evidence for a spin-up between the two RXTE observations with \( P = 5.93 \times 10^{-7} \) s\(^{-1} \) (Krimm et al. 2013). Archival data of XMM–Newton and the BeppoSAX Phoswich Detector System (PDS) have also shown the presence of the source at a flux of \( 7 \times 10^{-13} \) erg cm\(^{-2} \) s\(^{-1} \) in 2–10 keV on 2003 March 8 (Halpern & Gotthelf 2008) and at a flux of \( 3.6 \times 10^{-11} \) erg cm\(^{-2} \) s\(^{-1} \) in 15–30 keV on 1998 September 29 (Orlandini & Frontera 2008), respectively. The companion star has not yet been identified; archival searches in the Chandra region of the X-ray source were unable to reveal any optical/near-infrared counterpart (Krimm et al. 2013).

This letter is organized as follows. In Section 2, we describe the Swift data reduction. In Section 3, we report on the timing analysis. In Section 4, we describe the broad-band spectral analysis. In Section 5, we briefly discuss our results.

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2 OBSERVATIONS AND DATA REDUCTION

The Swift BAT survey raw data collected between 2004 December and 2014 June were processed with dedicated software (Segreto et al. 2010) that computes all-sky maps in several energy bands between 15 and 150 keV, performs source detection on these maps and, for each detected source, produces standard products, such as light curves and spectra. Swift J1816.7–1613 was inside the BAT field of view for a total of 38.1 Ms. The source was detected in the 15–150 keV all-sky map with a signal-to-noise ratio (S/N) of 10.1 standard deviations, and of 12.8 standard deviations in the 15–45 keV all-sky map, where its S/N is maximized. The latter energy band was used to extract the light curve with the maximum time resolution (∼300 s) allowed by the Swift BAT survey data. The spectrum is extracted in eight energy channels and analysed using the official BAT spectral redistribution matrix.

The Swift X-Ray Telescope (XRT; Burrows et al. 2004) observed Swift J1816.7–1613 seven times. The source was observed in Photon Counting (PC) mode (Hill et al. 2004) in all the observations, for a total exposure time of ∼10.7 ks. The details on the Swift XRT observations are reported in Table 1. The XRT data were processed with standard procedures (XRTPIPELINE v.0.12.8) using FTOOLS in the HEASOFT package (v.6.15) and the products were extracted adopting a circular region of 20 pixel radius (one pixel = 0.236 arcsec) centred on the Chandra source position, while the background for spectral analysis was extracted from an annular region centred on the source, with an inner radius of 70 pixels and an outer radius of 130 pixels, to avoid contamination due to the point spread function tail of Swift J1816.7–1613. All source event arrival times were converted to the Solar system barycentre with the task BARYCORR. The XRT ancillary response files for each observation were generated with XRTMKARF.3Besides spectra for each single XRT observation, we also extracted a cumulative source and background spectrum from all the spectra were re-binned with a minimum of 20 counts per energy channel, in order to allow the use of the χ^2 statistics. We used the spectral redistribution matrix v.014 and the spectral analysis was performed using XSPEC v.12.5. Errors are at 90 per cent confidence level for a single parameter, if not stated otherwise.

3 TIMING ANALYSIS AND RESULTS

Fig. 1 shows the light curve of Swift J1816.7–1613 in the 15–45 keV band, between 2004 November and 2014 June (with a bin of length of 15 d), where several outburst episodes of similar duration (∼30 d) and intensity are visible. This behaviour is suggestive of a Be/X-ray binary system (as already suggested by Corbet & Krimm 2014) where the appearance of Type I outbursts is related to the periastron passage of the compact object. The similarity of all the observed flares, both in duration and in intensity, suggests that none of them is a Type II outburst uncorrelated with the orbital modulation. The outbursts peak times are MJD 53 745 ± 30, 54 088 ± 9, 54 556 ± 1.0, 55 041 ± 1.0, 55 742 ± 1.5, 56 224 ± 1.0, 56 816 ± 1.0, where the peak time and its error are evaluated by fitting a Gaussian to the relevant portion of the light curve (produced with a bin time of 5 d). The larger uncertainties in the first and second outbursts are due to the fact that they are detected with lower significance, because they are covered only partially by the survey data. According to the sequence of outbursts observed during our monitoring, the periodicity, if any, is constrained to be a submultiple of the distance between any pair of consecutive outbursts. This is evident when we observe that the time interval between the second pair of outbursts (∼470 d) is not a multiple of the time interval between the first two outbursts (∼340 d, the shortest interval in the sequence).

In order to verify if the appearance of these outbursts has a periodic behaviour, we have performed a timing analysis on this light curve using the folding technique (Leahy, Elsner & Weisskopf 1983). This technique consists of the production of a count rate profile for a set of trial periods by folding the count rates in N phase bins and in the evaluation of the χ^2 value with respect to the average count rate for the profile corresponding to each trial period. A large value of χ^2 represents a clue of a periodic modulation. The periodogram has been produced in the 1–1000 d period range with a step of P0/(N ΔT_BAT) (where P is the trial period, N = 16 is the number of phase bins used to build the profile and ΔT_BAT ∼ 298.2 Ms is the data time-span). This periodogram (Fig. 2) is quite noisy for test periods higher than ∼100 d. A few peaks emerge over the noise, although none of them has enough power to be claimed as a strong indication of periodicity, or is consistent with either 151.4 d (Corbet & Krimm 2014) or being a submultiple of both 340 and 470 d. We have then repeated the folding analysis after selecting from the light curve only 200-d data intervals centred on the observed outbursts. This selection allows us to exclude light-curve intervals that would introduce only noise in the following timing analysis, and still explore the possible range of outburst periodicities.

Fig. 3 (top panel) shows the periodogram obtained from the selected data, where a prominent feature emerges at ∼118 d. Its peak can be fitted with a Gaussian function (Fig. 3, inset in top

Table 1. XRT observations log. The quoted orbital phase refers to the profile reported in the lower panel of Figure 3, bottom panel.

| Obs no | Obs ID     | T_start MJD | T_elapsed (s) | Exposure (s) | Rate (c s⁻¹) | Orb. phase | Spin period (s) |
|--------|------------|-------------|---------------|--------------|--------------|------------|----------------|
Orbital period of Swift J1816.7–1613

Figure 1. BAT light curve in the 15–45 keV band. The bin length corresponds to a time interval of 15 d. The vertical shaded areas are separated by 118.5 d and are in phase with the peak position of the brightest outburst at MJD 54 556.1.

Figure 2. Periodogram of Swift BAT (15–45 keV) data for Swift J1816.7–1613. The arrow marks the period suggested by Corbet & Krimm (2014).

Figure 3. Top panel: periodogram obtained by selecting only 200-d time intervals centred on the observed outbursts; the period suggested by Corbet & Krimm (2014) is marked with an arrow. The inset shows a close-up view of the periodogram around $P_0 = 118.5$ d and the best-fitting Gaussian function to the peak. Bottom panel: Swift BAT light curve folded with a period of $P_0$ in 30 phase bins, selecting only 200-d time intervals centred on the observed flares.

panel), obtaining a peak centroid at $P_0 = 118.5 \pm 0.8$ d, where the error is the standard deviation of the best-fitting Gaussian. This value is consistent with it being a submultiple of both the two shortest time intervals between the outbursts ($\sim 340$ and $\sim 470$ d).

The bottom panel of Fig. 3 shows the pulse profile obtained by folding the data in 30 phase bins with a periodicity of $P_0$ and $T_{\text{epoch}} = \text{MJD} 55 216.6$. The profile shows a narrow peak emerging by at least two orders of magnitude over a flat plateau whose intensity is marginally above zero. The peak is at phase $0.48 \pm 0.5$ and corresponds to MJD $(55 273.7 \pm 2)$ $\pm n \times P_0$, where the uncertainty is half of a phase bin.

Table 1 reports the average count rate recorded during the XRT observations and the relevant orbital phase evaluated with respect to $P_0$ and $T_{\text{epoch}}$. Observations 1–3 performed by XRT on Swift J1816.7–1613 correspond to the flare peaking at MJD 54 556 in Fig. 1, observations 4–6 correspond to the end tail of the same flare, while observation 7 is just before the flare peaks at MJD 56 224.

We performed a timing analysis on the XRT data, searching for the presence of the periodic modulation detected by Chandra (Halpern & Gotthelf 2008) and confirmed by RXTE (Krimm et al. 2013). XRT observations are fragmented into snapshots of different durations and time separations. This causes spurious features to emerge when the timing analysis is performed on data belonging...
to more than one snapshot, and affects the detection of a source periodic signal. To avoid these systematics, we have performed a folding analysis separately on each snapshot, searching in a period range 100–200 s. The periodic modulation has been revealed in the periodograms derived from the snapshots of observations 1, 2 and 3 (Table 1); the statistics content in the other XRT observations is too poor to allow for a periodic modulation to emerge over the noise.

In each snapshot periodogram, a period was associated with the centroid of the Gaussian that best fitted the revealed feature, while the error is evaluated applying equation (6.3a) in Leahy (1987). The period relevant to each observation was then evaluated by weighting the periods relevant to each snapshot with the inverse square of their errors. Table 1 lists the resulting periods. The period averaged among observations 1, 2 and 3 is 143.2 ± 1.1 s.

4 SPECTRAL ANALYSIS

As shown in Fig. 1, BAT observed several outburst episodes during its monitoring of Swift J1816.7–1613. Selecting only the data in these intervals (30-d time intervals centred on the peak times of the outbursts), the source is detected at a significance level of about 30 standard deviations, while outside these outbursts Swift J1816.7–1613 shows a weak emission below the detection threshold (S/N ~ 4).

We have performed a broad-band spectral analysis relevant to the periods of outburst emission. First, we verified that no significant spectral variability is present among XRT observations 1–3 and among the outbursts observed by the BAT; fitting each XRT spectrum with an absorbed power law, we found that both the best-fitting absorption columns and photon indices were consistent within the statistical errors. The BAT spectra relevant to each flare episode, fitted with a simple power law, also showed no significant spectral variation. Therefore, we summed the XRT data of observations 1–3 and the BAT data collected during all the outburst episodes, and combined the resulting XRT and BAT spectra to perform a broad-band spectral analysis. Trial models were multiplied by a constant to account for any intercalibration uncertainty between the two telescopes and for different flux levels among the two spectra. This constant was frozen to unity for the XRT spectrum and was left free to vary for the BAT spectrum.

An absorbed power-law model ($\text{cutoffpl}$) was rejected because of its unacceptable $\chi^2$ of 221 over 83 degrees of freedom (d.o.f.). The fit is significantly improved by including a cutoff in the above model ($\text{phabs*cutoffpl}$), with a resulting $\chi^2$ of 92 over 82 d.o.f., and an $F$-test probability of $\sim 3 \times 10^{-4}$ of obtaining this improvement by chance.

Fig. 4 shows the data and best-fitting model and the residuals, while Table 2 reports the best-fitting parameters.

5 DISCUSSION AND CONCLUSIONS

The light curve of Swift J1816.7–1613 is characterized by a sequence of very bright outbursts lasting ~30 d, and by long quiescent time intervals. During the 113 months of BAT survey monitoring, we observe seven outbursts that we find to have a periodicity $P_0 = 118.5 \pm 0.8$ d, which we interpret as the orbital periodicity of the source. Our result is at odds with the periodicity of $\sim 151$ d obtained by Corbet & Krimm (2014). To compare the two results, we have analysed the phase $\phi$ of each of the observed outbursts with respect to $P_0 = 118.5 \pm 0.8$ d and to $P = 151.4 \pm 1$ d, and we have plotted the residual phase $\phi - \langle \phi \rangle$, where $\langle \phi \rangle$ is the average phase value for the set of observed outbursts with respect to each of the two periods (Fig. 5). The latter values are all expected to be consistent with $0$ if the test periodicity describes well the outburst sequence. If we apply a $\chi^2$ test to the residual phases, assuming an expected value of 0, we find a reduced $\chi^2$ of 0.5 for $P = 118.5$ d and 3.1 for $P = 151.4$ d. The higher $\chi^2$ obtained for $P = 151.4$ d is mainly a result of the outburst at MJD 55 041, which is not consistent with this periodicity.
Figure 6. Corbet diagram for high-mass X-ray binaries with known spin and orbital period. Diamond and star points represent the Be and supergiant systems, respectively. The red filled circle marks the position of Swift J1816.7–1613.

The BAT light curve folded at $P_0$ is characterized by a narrow peak emerging over a flat plateau, where the off-peak emission is at least two orders of magnitude lower than the peak intensity. The peak has a duration of $\sim 30$ per cent of $P_0$, corresponding to $\sim 30$ d. Thus, the emission of this source is concentrated in a short fraction of its orbit. Moreover, the outbursts do not occur at every cycle: in the sequence observed during our monitoring, they are separated by three to six cycles. This behaviour is commonly observed in X-ray binaries with a Be star as a companion. These stars are likely to be characterized by an equatorial extended disc, fed from material ejected from the star itself because of its rapid spin rotation (see Reig 2011 for a recent review). In such binary systems, the stellar disc is often oriented on a plane different from the orbital plane of the neutron star. Periodic or quasi-periodic outbursts, lasting a fraction of 10–30 per cent of the orbital period, peaking close to the periastron passage of the neutron star, are the consequence of an enhancement of the accretion flow from the companion star as it passes close to the circumstellar disc. The position of Swift J1816.7–1613 on the Corbet diagram (Corbet 1986) in Fig. 6 shows that the source lies in the Be transient region, adding a further strong hint concerning its nature as a Be/X-ray binary system.

A timing analysis on the XRT data confirms the presence of the periodic modulation first revealed by Chandra (Halpern & Gotthelf 2008) and confirmed by RXTE follow-up observations (Krimm et al. 2013). The spin periodicity, detected in the XRT observations 1, 2 and 3 is $143.2 \pm 1.1$ s.

Finally, the broad-band 0.2–150 keV spectrum collected during the outbursts is modelled with an absorbed power law with a flat photon index $\Gamma \sim 0.1$ and a steepening in the BAT energy range modelled with a cut-off at an energy of $\sim 10$ keV, and an average flux of $(1.30 \pm 0.08) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. The spectrum is strongly absorbed, with a column density one order of magnitude higher than the average value along the line of sight (Dickey and Lockman 1990). Assuming this same spectral shape, the off-outburst average flux is $(2.9 \pm 1.1) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

ACKNOWLEDGEMENTS

This work has made use of data retrieved through the HEASARC Browse Mission Interface, a service provided by the Astrophysics Science Division at NASA/GSFC and the High Energy Astrophysics Division of the Smithsonian Astrophysical Observatory. This work has been supported by ASI grant I/011/07/0.

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