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Swift and SALT observations of the multiple outbursts of MAXI J1957+032

D. Mata Sánchez,[1,2]★ P. A. Charles,[1,3] M. Armas Padilla,[1,2] D. A. H. Buckley,[4] G. L. Israel,[5] M. Linares[1,2] and T. Muñoz-Darias[1,2]

[1]*Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain*
[2]*Departamento de astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain*
[3]*Department of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK*
[4]*South African Astronomical Observatory, PO Box 9, 7935 Observatory, Cape Town, South Africa*
[5]*INAF – Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monteporzio Catone, Italy*

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ABSTRACT

The new recurrent X-ray transient MAXI J1957+032 has had four X-ray outbursts within 16 months, all very briefly detected (lasting <5 d). During the most recent event (2016 September/October), we obtained with the Southern African Large Telescope the first optical spectrum of the transient counterpart, showing the classic blue continuum of an X-ray irradiated disc in an LMXB and no other features. At high Galactic latitude below the plane (−13°) reddening is low but there is no quiescent counterpart visible on any of the existing sky surveys, nor any other known X-ray source in the region. *Swift* monitoring of three of the four events is presented, showing rapidly fading X-ray outbursts together with significant UVOT detections in the *UV* (*W1*,*M2*,*W2*), *U* and *B* bands. The optical properties are most like those of the short-period LMXBs, which, combined with the softening witnessed during the decay to quiescence would place the system at $d < 13$ kpc. The short duration and short recurrence time of the outbursts are reminiscent of the accreting millisecond X-ray pulsars, which exhibit peak luminosities of ∼1 per cent L_{Edd}. Assuming this peak luminosity would place MAXI J1957+032 at a distance of $d \sim 5$–6 kpc.

Key words: accretion, accretion discs – X-rays: binaries.

1 INTRODUCTION

The highly variable X-ray sky is populated with X-ray transients (XRTs). These are usually classified as objects typically in quiescence with X-ray luminosities well below 10^{33} erg s^{-1}, which increase by several orders of magnitude during outbursts. Within our Galaxy, luminous XRT behaviour is demonstrated by both high-mass and low-mass X-ray binaries (HMXBs and LMXBs, respectively), where the former are predominantly BeX systems involving neutron stars (NSs) in long (tens of days or more) eccentric orbits around a rapidly rotating Be star (e.g. Reig 2011). As we will show, the properties of J1957 are consistent with that of LMXB transients, which contain either a black hole (BH) or NS in a close (typically $P_{orb} \sim$ hours) circular orbit with a low-mass, evolved donor (Remillard & McClintock 2006; Liu, van Paradijs & van den Heuvel 2007).

Since the demise of the *RXTE* all-sky monitor (ASM) in 2012, the X-ray sky monitoring task has been shared between the *INTEGRAL*, *Swift* and *MAXI* missions. Thanks to their wide field and all-sky monitoring programs (Kuulkers et al. 2007; Krimm et al. 2013 and Matsuoka et al. 2009, respectively), the last decade has seen the emergence of a number of new XRTs (Swift J1753.5−0127, MAXI J1659−152, Swift J1357.2−093313, MAXI J1305−704) at high Galactic latitude and subsequently found to have short periods (≤5 h). Combined with the already well-known XRTs, GRO J0422+32 and XTE J1118+480, this suggested the existence of a possible sub-group of LMXB XRTs, whose high latitude (and consequent low extinction) made them important targets for multiwavelength studies (see e.g. Shaw et al. 2013). Furthermore, since many of these XRTs are too faint in quiescence for current telescopes (especially the short period systems which tend to have the lowest mass donors), it is very important to undertake rapid follow-up optical spectroscopy while the X-ray outburst is underway, as it can then be possible to exploit the X-ray irradiation of the donor to provide constraints on the motion of the donor (see e.g. Cornelisse 2013).

The high-latitude XRT MAXI J1957+032 (hereafter 'J1957') was discovered in 2015, independently by both *MAXI* (Negoro et al. 2015) and *INTEGRAL* (Cherepashchuk et al. 2015, who designated the source IGR J19566+0326), and optically identified (Rau,

★ E-mail: dmata@iac.es

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Yates & Greiner 2015) with a faint $r' \sim 20$ star, there being no counterpart on sky-survey images (Chakrabarty, Jonker & Markwardt 2016). However, that and the subsequent two outbursts over the next year (Sugimoto et al. 2015; Tanaka et al. 2016[1]), decayed rapidly (within a matter of days), making extensive follow-up study almost impossible. Nevertheless, Marchesini et al. (2015) described a low-resolution (∼17 Å) optical spectrum of J1957 taken during the 2015 October outburst (where Guver et al. 2015 had reported $R = 18.3$ four days after the start of the outburst), which contained only absorption features consistent with an F-/G-type star, and no emission lines. This was surprising, as virtually all LMXB XRTs in outburst have optical spectra that are dominated entirely by the X-ray irradiated accretion disc, producing a strong blue continuum on which is usually superposed strong Balmer, HeII and Bowen emission features (see e.g. Charles & Coe 2006).

Furthermore, to have three X-ray outbursts within a year is unusual amongst the class of LMXB XRTs; so, when a new, brighter X-ray outburst of MAXI J1957+032 was reported in 2016 September (Negoro et al. 2016), we immediately initiated our SALT Transients ToO program (Buckley et al. 2016) in order to obtain further optical spectra of this intriguing object. Those data, together with the associated *Swift* monitoring of J1957, are the subject of this paper.

2 OBSERVATIONS

Due to the short duration and faintness of J1957 outbursts, both *MAXI*/GSC (2–20 keV) and *Swift*/BAT (15–50 keV) light curves do not exhibit any remarkable feature (e.g. rebrightening) other than the reported starting times of the four events. These correspond to 57153.58 (2015-05-11, epoch 1), 57301.52 (2015-10-06, epoch 2), 57394.35 (2016-01-07, epoch 3) and 57660.35 (2016-09-29, epoch 4); three of them marked in Fig. 1.

2.1 *Swift*/XRT

2.1.1 Spectral analysis

Following the outburst alerts, the X-ray Telescope (hereafter Swift/XRT; Burrows et al. 2005) on board *Swift* (Gehrels et al. 2004) covered three of the four reported events. A total of 28 observations [two in window timing (WT) mode and the rest in photon counting (PC) mode] were performed, but due to the outburst rapid decline, J1957 is detected in only 10 of these observations. We processed the data making use of the HEASOFT v.6.18 software. The data reduction was carried out running the XRTPIPELINE task in which standard event grades of 0–12 and 0–2 were selected for the PC and WT mode observations, respectively. For each observation, the 0.5–10 keV spectrum, light curve and image were obtained using XSELECT. We used a circular region of ∼40-arcsec radius centred at the source position (the inner 10 arcsec were excluded for 00033770019 observation, 57662.75, affected by pile-up). For the PC observations, three circular regions of similar size and shape, positioned on an empty sky region, were used for the background. On the other hand, an annulus centred on the source with ∼82 pixels for the inner radius and ∼118 pixels for the outer radius was used for the background of the WT observations. We created exposure maps and ancillary response files following the standard *Swift* analysis threads,[2] and we

[1] Note that the 2–20 keV fluxes quoted for January 7 and 8 are incorrect. They should have been 0.066 and 0.071 ph cm^{-2} s^{-1}, respectively.
[2] http://www.swift.ac.uk/analysis/xrt/

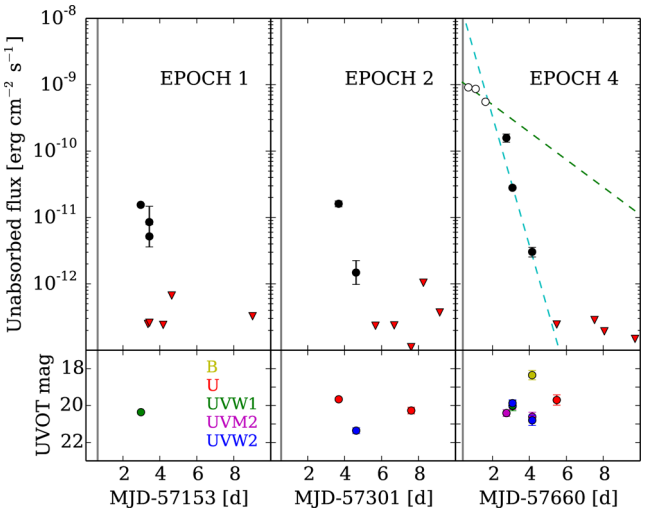


Figure 1. Upper panel: Detailed *Swift*/XRT (0.5–10 keV) monitoring of J1957 events 1, 2 and 4. The most detailed coverage is of event 4, where we also plot exponential decays of e-folding time-scales 2.1 ± 0.9 and 0.44 ± 0.15 d to the slow and fast declines, respectively. Empty circles refer to WT mode and filled circles to PC mode observations. The start times of the covered outbursts are marked by vertical dashed lines. Lower panel: *Swift*/UVOT (*B*, *U*, *UW1*, *UM2* and *UW2* filters) follow-up pointings are shown.

acquired the last version of the response matrix files from the High Energy Astrophysics Science Archive Research Center (HEASARC) calibration data base (CALDB). Finally, we grouped the spectra to have a minimum of 20 photons per bin to be able to consistently use the χ^2. However, due to the low number of counts collected during various observations, we fitted these data using both C statistic and χ^2 but grouped them with a minimum of five photons per bin (see Table 1). The results using both methods were consistent with each other (e.g. Wijnands & Wang 2002; Armas Padilla et al. 2013). We fitted the spectra using XSPEC (v.12.9, Arnaud 1996). All observations were well fitted with a simple power law (PL) plus absorbing column (PHABS in XSPEC) assuming the cross-sections of Verner et al. (1996) and the abundances of Wilms, Allen & McCray (2000). We assumed a constant hydrogen equivalent column density of $N_{\rm H} = 1.7 \times 10^{21}$ cm^{-2}, inferred from our highest signal-to-noise spectrum (Fig. 2) and consistent with the low reddening expected for that direction (see next section). The photon-index of each spectrum's fit varies from 1.90 ± 0.02 to $2.34^{+0.27}_{-0.25}$ (from highest to lowest luminosity). The unabsorbed fluxes are reported in Fig. 1. We note that observation 00033770018 (57661.09) consists of two ∼ 350 s-long groups of detections ∼13 h apart (similar to the gap between the first group and the previous observation, ∼14 h), so we decided to plot two independent points in the light curve.

For the observations where J1957 is not detected, we determined the 95 per cent confidence upper-limit count rates using the prescription given by Gehrels (1986). We estimated the corresponding unabsorbed flux upper limits using the WEBPIMMS HEASARC tool. We co-added 10 *Swift*/XRT (PC mode) observations (11.7 ksec) in order to constrain the quiescent luminosity of MAXI J1957+032. We can thereby place a 95 per cent confidence upper limit on the 0.5–10 keV quiescent unabsorbed flux of (1–3) × 10^{-13} erg cm^{-2} s^{-1} (assuming $N_{\rm H} = 1.7 \times 10^{21}$ cm^{-2} and a PL photon index in the 1–3 range). Comparing with the epoch 4 detection at a flux of ∼ 10^{-9} erg cm^{-2} s^{-1}, this reveals that the X-ray luminosity dropped by at least four orders of magnitude in just about a week.

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Table 1. *Swift* observations log and spectral results for J1957 using a PHABS*PO model. We assumed a constant $N_{\rm H}$ of 1.7×10^{21} cm^{-2}, inferred from the highest signal-to-noise spectrum (00033770017).

ID	MJD	Mode	Exposure (ks)	Γ	*unabs*, $F_{\rm X}$ (0.5–10 keV) (erg cm^{-2} s^{-1})	χ^2_ν (dof)
00033770001	57155.96	PC	2.9	2.13 ± 0.07	$(1.55 \pm 0.08) \times 10^{-11}$	0.97 (167)
00033776001	57156.42	PC	0.44	1.5 ± 0.6	$(8.5\ ^{+6.2}_{-3.7}) \times 10^{-12}$	0.36 (5)
00033777001	57156.43	PC	0.45	2.5 ± 0.8	$(5.2\ ^{+2.6}_{-1.6}) \times 10^{-12}$	0.91 (6)
00033770009	57304.67	PC	0.96	2.0 ± 0.1	$(1.61 \pm 0.16) \times 10^{-11}$	1.11 (67)
00033770010	57305.61	PC	0.98	2.6 ± 0.9	$(1.5\ ^{+0.7}_{-0.5}) \times 10^{-12}$	1.54 (5)
00033770017	57660.69	WT	0.97	1.90 ± 0.02	$(9.13 \pm 0.13) \times 10^{-10}$	1.02 (364)[b]
00033770018[a]	57661.09	WT	0.77	1.92 ± 0.02	$(7.09 \pm 0.12) \times 10^{-10}$	1.04 (304)[b]
00033770018-1[a]	57661.09	WT	0.45	1.92 ± 0.03	$(8.65 \pm 0.18) \times 10^{-10}$	1.18 (252)[b]
00033770018-2[a]	57661.62	WT	0.33	1.93 ± 0.04	$(5.53 \pm 0.18) \times 10^{-10}$	0.89 (153)[b]
00033770019	57662.75	PC	0.37	1.89 ± 0.2	$(1.58 \pm 0.22) \times 10^{-10}$	0.84 (80)
00033770020	57663.08	PC	1.7	1.94 ± 0.07	$(2.80 \pm 0.17) \times 10^{-11}$	1.22 (164)
00033770021	57664.14	PC	1.7	2.3 ± 0.3	$(3.03 \pm 0.49) \times 10^{-12}$	0.97 (27)

Notes. [a]Observation 00033770018 was divided in two sub-events of detections ∼13 h apart (see Section 2.1.1).
[b]Spectra with a minimum of 20 photons per bin. The rest are grouped with a minimum of 5 photons per bin (see Section 2.1.1).

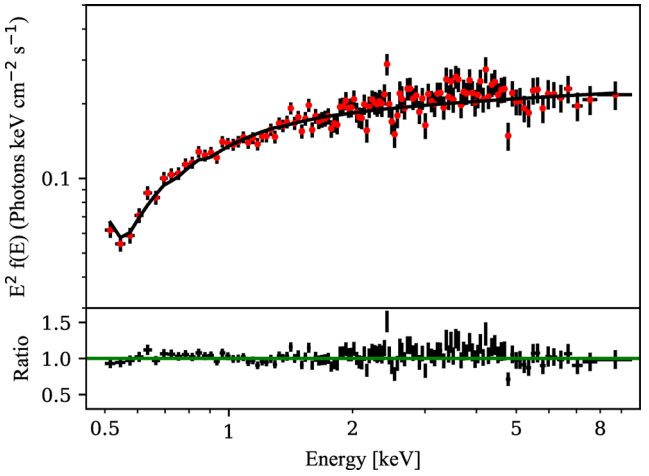


Figure 2. Unfolded spectra of observation 00033770017 (57660.69, 2016-09-29). The solid line represents the best fit using a PHABS*POWERLAW model. The sub-panel shows the data-to-model ratio. Data have been re-binned in XSPEC for clarity.

2.1.2 Timing Analysis

We searched for pulsations and quasi-periodic oscillations in the three *Swift*/XRT observations with WT mode data (1.78 ms time resolution). These were taken on 57160 (2015-05-18, 1.3-ksec exposure), 57660 (2016-09-29, 1 ksec) and 57661 (2016-09-30, 0.8 ksec). We used 30- and 120-s-long Fast Fourier Transforms (FFTs), including energies between 1 and 10 keV, keeping the original time resolution and inspecting individual FFTs as well as observation averages. We detect neither coherent pulsations nor aperiodic variability in the 0.1–281 Hz frequency range. The most constraining upper limits come from the 57660 observation, when the average 1–10 keV count rate was ∼16.5 count s^{-1} . Following Vaughan et al. (1994), we estimate upper limits on the pulsed fraction of a sinusoidal signal. We find upper limits on the 0.1–281 Hz pulsed fraction between 2.2 per cent and 5.4 per cent (95 per cent confidence level), depending on the FFT length and exact frequency range. We note that, considering the pulsed fractions and spin frequencies of the accreting millisecond X-ray pulsars (AMXPs) (e.g. Patruno & Watts 2012, and references therein), this result does not exclude the presence of similar pulsations in J1957.

2.2 *Swift*/UVOT

There were also optical/UV observations of J1957 associated with many of the Swift/XRT pointings, and these were accessed from the Swift online archive. We used the UVOTSOURCE software (released as part of the HEASOFT package) to extract fluxes for J1957 using a 5-arcsec aperture centred at the position reported in Rau et al. (2015). J1957 was not detected in the *V* band, our best constraint being $V > 17.85$ (MJD 57665.5). At different times it was seen in all other bands, with the brightest detections being $B = 18.5 \pm 0.3$ (MJD 57664.1), $U = 18.7 \pm 0.3$ (MJD 57665.5), $UVW1 = 18.5 \pm 0.3$, $UVM2 = 18.3 \pm 0.2$ and $UVW2 = 18.1 \pm 0.2$ (MJD 57663.1). All values are Vega magnitude and were obtained during epoch 4. Using the relation $N_{\rm H} = 2.0 \pm 0.5 \times 10^{21}$ cm^{-2}, $A_{\rm V}$ (Watson 2011) and the Galactic hydrogen column density $N_{\rm H} = 0.95 \times 10^{21}$ cm^{-2} [which yields $E(B-V) = 0.14$, Willingale et al. 2013, we obtain $A_V \sim 0.5$ and $A_B \sim 0.6$. This implies that the brightest *B*-band detection corresponds to an intrinsic value of $B = 17.9 \pm 0.3$. We note that using a 5-arcsec aperture includes star '1' (see Fig. 3), classified as an A-F star ($R = 18.3$). It makes a small contribution in the *B* band ($B > 19$), has no effect in the *UV* bands, but affects *V*-band observations, which will be disregarded.

2.3 SALT imaging and spectroscopy

We obtained optical imaging of J1957 with the Southern African Large Telescope (SALT, Buckley, Swart & Meiring 2006) on 57662.76 (2016-10-01, epoch 4), 2.4 d after the initial X-ray outburst report (Negoro et al. 2016). We used SALTICAM (O'Donoghue et al. 2006) to obtain a 60 s r'-band image (Fig. 3), which showed the previously identified optical counterpart (Guver et al. 2015; Marchesini et al. 2015) to be at $r' = 18.5 \pm 0.15$, similar to the $R = 18.27$ reported 4.2 d after the 2015 October outburst (Guver et al. 2015), and brighter than the $r' = 20.03$ measured 3.7 after the 2015 May outburst (Rau et al. 2015).

With this clear indication of renewed optical activity, we then immediately followed this with a 1000 s exposure spectrum using the SALT Robert Stobie Spectrograph (RSS). This was taken with the 300 l mm^{-1} grating (mean resolving power of 320) covering 360–770 nm and through a 1.5 arcsec slit [the PSF was 1.3 arcsec full width at half-maximum (FWHM)], oriented as shown in Fig. 3 so as to exclude light from the nearby star '1' (2.0 arcsec to the

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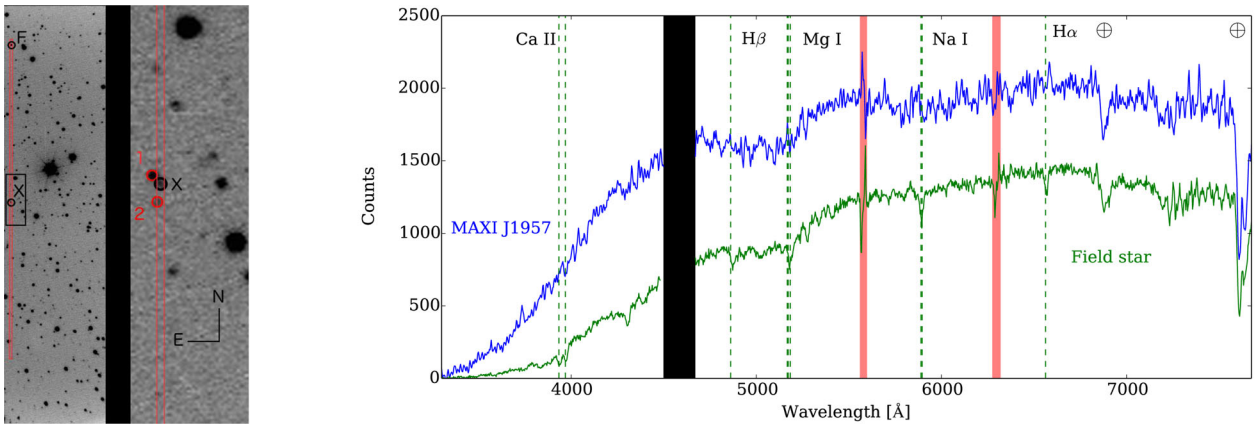


Figure 3. Left-hand panel: part of the SALTICAM r'-band image (left) of the region of J1957 (marked with 'X' and a black circle) showing the orientation of the RSS long slit (red box) and the field star 'F' that was included. The black box is blown up (right) so as to show the location of J1957 and its nearby stars marked '1' and '2', circled in red. Right-hand panel: RSS low-resolution spectra of J1957 (upper) and the simultaneously observed brighter field star ('F') whose flux has been reduced by × 7 to facilitate comparison. 'F' is a late-G star in the USNO catalogue (see text) and the key spectral features are marked as green-dashed lines. Telluric features are marked with the symbol ⊕ and sky-subtraction residuals as red-shadowed bands. There are no cosmic features in J1957, but it is noticeably bluer than 'F'. Colour figures are available in the online version.

NE of J1957). These data, together with associated arcs and bias frames were processed and reduced with the standard SALT pipeline (Crawford et al. 2010), followed by cosmic ray removal using the IRAF[3] task 'L. A. Cosmic' (van Dokkum 2001) on the 2D image. We then extracted the spectrum of J1957 and other stars within the slit using standard IRAF routines. Wavelength calibration was performed using arc spectra with the MOLLY routines `arc` and `acal`, and the results are in Fig. 3.

The spectrum of J1957 is essentially featureless (apart from telluric lines), notably so in comparison with field star 'F', which was simultaneously in the slit. This star is USNO-B1.0 0935-0543890, of observed spectral type G5-K0 and with $B = 18.3$, $B-R = 1.2$, which we have used with our spectra to estimate $B-V = 0.3$ for J1957 (significantly bluer than 'F' in our spectrum for which we obtain $B-V = 0.7$). X-ray active LMXBs have optical spectra dominated by the X-ray irradiated disc, and often have strong Balmer and HeII lines in their spectra. However, the more compact systems, especially those seen at high inclination, have much weaker emission lines, often almost completely undetectable (e.g. Baglio et al. 2016). Indeed, ultracompact systems accretion discs should be depleted of hydrogen, as the companion star is itself degenerate (see Nelemans & Jonker 2010). We constrain the equivalent width of the H α line to be lower than 3 Å at 3σ confidence level (assuming a conservative FWHM < 4400 Å determined by the widest Hα profile measured so far in a LMXB, see Mata Sánchez et al. 2015).

As already reported (Buckley et al. 2016), our spectrum contrasts with the A-F star absorption features reported by Marchesini et al. (2015) using the Nordic Optical Telescope (and ALFOSC) at a similar resolution 8.2 d after the epoch 2 outburst (2015 October). We re-analysed the ALFOSC data of this epoch, and from a 250 s image taken immediately after the spectrum, obtained $R = 21.4 \pm 0.2$ for J1957. This led to the realization that the reported Nordic Optical Telescope (NOT) spectrum was not of J1957, but rather of star '1', 2.0 arcsec NE of J1957. We measured star '1' to have $r' = 18.0 \pm 0.15$ and $R = 18.3 \pm 0.1$, respectively, from the SALTICAM and ALFOSC images taken a year apart, and is consistent with the fluxes measured in the NOT spectrum. All of the photometry reported here used the same reference star, USNO B1.0 0934-0560330.

[3] IRAF is distributed by National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

3 DISCUSSION

Having resolved the question of the spectroscopic identification of J1957, and demonstrated that its optical spectrum is consistent with other LMXB XRTs in their active phase, the *Swift*/XRT light curve highlighted the extremely rapid decay of the outburst (and which Fig. 1 shows was likely the case for all the outbursts). The essential properties of this object are straightforward to summarize: (i) outburst light curves that increase rapidly (within a *MAXI* orbit we change from non-detection to the peak luminosity) and decay steeply, lasting < 5 d in total; (ii) no detected rapid variability or type I X-ray bursts during their bright phase; (iii) have an associated optical brightening from quiescence of ≥ 3 mags; and (iv) hard X-ray spectrum (not that of a disc blackbody). With these properties at hand, we can rule out the following classifications for J1957:

(i) HMXB/BeX system: The outbursts of J1957 have already been noted to be non-periodic (Tanaka et al. 2016), and the large range of optical variability (combined with our SALT spectrum) from quiescence rules out the possibility of an early-type donor;

(ii) Superburster: The longest 'superburst' is ∼0.3 d (in 't Zand 2011), much less than the 5 d of each J1957 outburst, and there would be enormous theoretical difficulties in producing sufficient nuclear fuel for such a superburst.

3.1 LMXB/XRT: comparison with Galactic Centre Region X-ray Transients

In spite of the extensive *RXTE*/ASM data base of XRT light curves (see e.g. Yan & Yu 2015), there are no BH LMXB/XRTs that display properties comparable to those of J1957. Within that same data base, only the NS system MXB 1730−335 (better known as the 'Rapid Burster') has a long-term light curve similar to that of J1957. Indeed, in the latter phases of the *RXTE* mission, MXB 1730−335 underwent six outbursts in barely 2 yr, each of which had a bright phase of usually <10 d. However, in its bright phase, this object

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emits most of its flux in the form of very rapid, type II X-ray bursts (e.g. Mahasena et al. 2003), which last only for 10 s or so. J1957 exhibits no such variations.

More recently, Degenaar et al. (2015) reported a 9 yr *Swift* X-ray monitoring of the Galactic Centre. During this campaign, various short outbursts (∼15 d long) were detected peaking at $L_X \sim 10^{35}$ erg s^{-1}, both from very faint as well as brighter LMXBs. However, none of these have a recurrence time as short as J1957.

Perhaps the most comprehensive monitoring campaign on Galactic X-ray transients took place in the period 1996–2000 when the *BeppoSAX* Wide Field Cameras (WFC, which had a 40° field of view) observed the Galactic Centre region nine times for a total exposure of ∼4 Ms. As summarized by in't Zand (2001), the combination of the *BeppoSAX* WFC observations and the *RXTE*/ASM data base led to the discovery of 31 LMXB XRTs that were active during this time interval. From this study (see their Table 2), there are four XRTs whose duration and peak X-ray flux are comparable to J1957. These are KS 1741−293, SAX J1748.9−2021, SAX J1750.8−2900 and SAX J1810.8−2609, all of whose outbursts lasted less than 10 d. However, subsequent *INTEGRAL* observations of the former (De Cesare et al. 2007) showed more extended periods of activity, and the latter two (Natalucci et al. 1999, 2000) both displayed Type I X-ray bursts with close to Eddington-limited properties. Despite J1957 not exhibiting any of those features, we note that either we could have missed the ignition of a hypothetical burst or maybe its outbursts are too short to trigger it. The remaining system SAX J1748.9−2021 is an AMXP spinning at 442 Hz in an 8.8-hr binary, and while it has recurrence times of order a year, the duration (of 8 d) was so similar in time-scale and light curve to J1957 that we decided to conduct a closer comparison with such objects.

3.2 Is J1957 an AMXP?

The most extensive review of AMXPs is that of Patruno & Watts (2012), in which we found N6440 X−2 to be very similar to J1957 both in recurrence time (∼1 month, the shortest recurrence time of any known XRT) and duration (3–5 d) of its outbursts (Heinke et al. 2010). The peak luminosities of the AMXPs are typically around 1 per centL_{Edd} (∼10^{36}erg s^{-1} for a 1.4 $M_\odot$ NS), which would place J1957 at $d \sim 6$ kpc. Indeed, comparing directly with N6440 X−2 places J1957 at $d \sim 5$ kpc. Another key similarity here is the light-curve shape of at least two AMXP (SAX J1808.4−3658 and IGR J00291+5934) during their (short, 1–2 weeks) periods of activity (see Fig. 1). They are characterized by an initial slow decay from the peak luminosity that ends with a sharp drop (see Hartman et al. 2008; Hartman, Galloway & Chakrabarty 2011). The knee of the light curve at a critical flux has been interpreted either as centrifugal inhibition of accretion or as the propagation of a cooling wave in the disc (Gilfanov et al. 1998). Assuming that these phenomena take place at the same luminosity level, we infer a distance to J1957 of $d \sim 5$–6 kpc (using $d = 3.5$ kpc for SAX J1808.4−3658 and $d = 4$ kpc for IGR J00291+5934).

There are three ultracompact AMXPs ($P_{orb} < 1.3$ h) known to have exhibited short (below 2 weeks) outbursts: N6440 X−2 (Altamirano et al. 2010), XTE J1751−305 (Grebenev, Molkov & Sunyaev 2005; Patruno & Watts 2012) and Swift J1756.9−2508 (Patruno, Altamirano & Messenger 2010); which favours the association of short outbursts with short orbital period LMXBs. Nevertheless, we note that at least three other AMXPs with longer periods that have exhibited similarly short outbursts: IGR J00291+5934 (Hartman et al. 2011; $P_{orb} = 2.5$ h reported by Markwardt et al. 2004), Swift J1749.4−2807 ($P_{orb} = 8.82$ h, see Wijnands et al. 2009 and Altamirano et al. 2011) and SAX J1748.9−2921 ($P_{orb} = 8.77$ h, Patruno et al. 2009). On the other hand, there are short period AMXPs like XTE J0929−314 (Remillard, Swank & Strohmayer 2002) and XTE J1807−294 (Markwardt, Juda & Swank 2003) which exhibited outbursts lasting several months. Despite the fact that these examples highlight the inexactness of the correlation between short outbursts and short orbital periods, we propose J1957 as a short period LMXB due to the combination of short duration outbursts, high recurrence time and featureless optical spectrum.

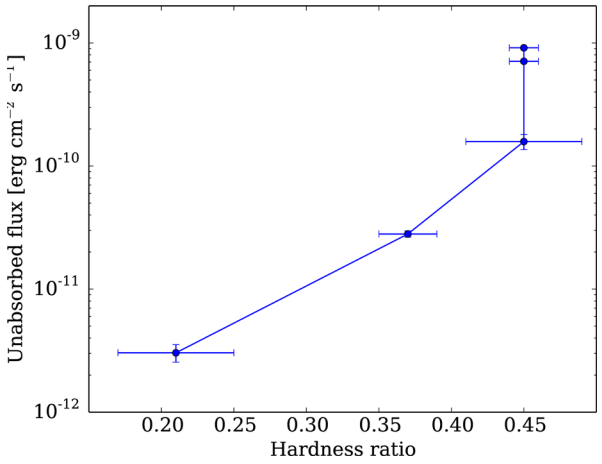


Figure 4. Hardness ratio for the Swift/XRT detections in the last outburst, defined as the ratio between (2–10 keV) and (0.5–2 keV) fluxes. The largest error point corresponds to the observation affected by pile-up (see Section 2).

Finally, assuming that the optical emission during active periods is dominated by an X-ray irradiated accretion disc, then we can use the X-ray/optical correlation equation of van Paradijs & McClintock (1994): $M_V = 1.57 - 2.27 \log \Sigma$, where $\Sigma = (L_X/L_{Edd})^{1/2}(P_{orb}[h])^{2/3}$ to derive an M_V for J1957 of 3.4, assuming a 2-h period. With our brightest B magnitude (see Section 2), this would imply a distance of about ∼7–9 kpc, somewhat closer if the period were shorter.

3.3 The X-ray spectrum

Hysteresis patterns between Compton-dominated and thermal-dominated states have been observed in both BH and NS LMXBs (e.g. Belloni, Motta & Muñoz-Darias 2011; Muñoz-Darias et al. 2014). These hysteresis phases, which are not witnessed in J1957, are observed at luminosities larger than ∼2 per cent L_{Edd} (see also Maccarone 2003). On the other hand, a softening phase during the decay towards quiescence is detected at lower luminosities (Plotkin, Gallo & Jonker 2013; Wijnands et al. 2015). In J1957, we do observe a softening in the hardness ratio as the luminosity decreases by, at least, a factor of ∼50 (see Fig. 4).

Indeed, if the softening of the source begins at 1.6×10^{-10}erg cm^{-2} s^{-1}, given that Wijnands et al. (2015) found this event always below 3×10^{36}erg s^{-1}, which would place J1957 at $d < 13$ kpc. On the other hand, the non-detection in quiescence of J1957 in the USNO-B catalogue (Monet et al. 2003), whose limiting magnitude in V is ∼21, implies a drop in luminosity of more than three magnitudes in the optical. If the donor is a dwarf star at a distance $d < 13$ kpc, its absolute magnitude is constrained to $M_V > 5.4$. Using Cox (2000) tabulated values, this results in a spectral type later than G7 (K6 if $d \sim 5$ kpc).

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4 CONCLUSIONS

Our X-ray and optical analysis suggests that MAXI J1957+032 is a short period LMXB, given the short duration and frequent recurrence of its outbursts, as well as the featureless optical spectrum. The spectral analysis leads us to place the system at $d < 13$ kpc, which combined with the non-detection of the quiescence counterpart results in a donor star spectral type later than G8. After comparing with the properties of other known XRTs, we find similarities with those of the AMXP class, which would place J1957 at $d \sim 5$ kpc. Further multiwavelength observations are encouraged especially taking into account the short recurrence times this system has exhibited in the past ∼1.5 yr.

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REFERENCES

Altamirano D. et al., 2010, ApJ, 712, L58
Altamirano D. et al., 2011, ApJ, 727, L18
Armas Padilla M., Degenaar N., Russell D. M., Wijnands R., 2013, MNRAS, 428, 3083
Arnaud K., 1996, in Jacoby G., Barnes J., eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems V. Astron. Soc. Pac., San Francisco, p. 17
Baglio M. C., D'Avanzo P., Campana S., Goldoni P., Masetti N., Muñoz-Darias T., Patiño-Álvarez V., Chavushyan V., 2016, A&A, 587, A102
Belloni T. M., Motta S. E., Muñoz-Darias T., 2011, Bull. Astron. Soc. India, 39, 409
Buckley D. A. H., Swart G. P., Meiring J. G., 2006, in Stepp L. M., ed, Proc. SPIE Conf. Ser. Ground-based and Airborne Telescopes. SPIE, Bellingham, p. 62670Z,
Buckley D. A. H., Kotze M. M., Charles P. A., Sanchez D. M., Munoz-Darias T., Israel G., Masetti E. J. M. N., Jonker P., 2016, Astron. Telegram, 9649
Burrows D. N. et al., 2005, Space Sci. Rev., 120, 165
Chakrabarty D., Jonker P. G., Markwardt C. B., 2016, Astron. Telegram, 9591
Charles P. A., Coe M. J., 2006, in Lewin W. H. G., van der Klis M., eds, Compact Stellar X-Ray Sources. Cambridge Univ. Press, Cambridge, p. 215
Cherepashchuk A. M., Molkov S. V., Lutovinov A. A., Postnov K. A., 2015, Astron. Telegram, 7506
Cornelisse R., 2013, in Pugliese G., de Koter A., Wijburg M., eds, ASP Conf. Ser. Vol. 470, 370 Years of Astronomy in Utrecht. Astron. Soc. Pac., San Francisco, p. 263
Cox A. N., 2000, Allen's Astrophysical Quantities. AIP Press, New York
Crawford S. M. et al., 2010, Proc. SPIE Conf. Ser. Vol. 7737, Observatory Operations: Strategies, Processes, and Systems III. SPIE, Bellingham, p. 773725
De Cesare G., Bazzano A., Martínez Núñez S., Stratta G., Tarana A., Del Santo M., Ubertini P., 2007, MNRAS, 380, 615
Degenaar N., Wijnands R., Miller J. M., Reynolds M. T., Kennea J., Gehrels N., 2015, J. High Energy Astrophys., 7, 137
Gehrels N. et al., 2004, ApJ, 611, 1005
Gilfanov M., Revnivtsev M., Sunyaev R., Churazov E., 1998, A&A, 338, L83
Grebenev S. A., Molkov S. V., Sunyaev R. A., 2005, Astron. Telegram, 446
Guver T. et al., 2015, Astron. Telegram, 8149
Hartman J. M. et al., 2008, ApJ, 675, 1468
Hartman J. M., Galloway D. K., Chakrabarty D., 2011, ApJ, 726, 26
Heinke C. O. et al., 2010, ApJ, 714, 894
in't Zand J., 2011, preprint (arXiv:1102.3345)
in't Zand J., 2001, in Gimenez A., Reglero V., Winkler C., eds, ESA SP-459: Exploring the Gamma-Ray Universe. ESA, Noordwijk, p. 463
Krimm H. A. et al., 2013, ApJS, 209, 14
Kuulkers E. et al., 2007, A&A, 466, 595
Liu Q. Z., van Paradijs J., van den Heuvel E. P. J., 2007, A&A, 469, 807
Maccarone T. J., 2003, A&A, 409, 697
Mahasena P., Inoue H., Asai K., Dotani T., 2003, Publ. Astron. Soc. Japan, 55, 827
Marchesini E. J., Israel G. L., Masetti N., Rodriguez G., 2015, Astron. Telegram, 8197
Markwardt C. B., Juda M., Swank J. H., 2003, IAU Circ., 8095
Markwardt C. B., Galloway D. K., Chakrabarty D., Morgan E. H., Strohmayer T. E., 2004, Astron. Telegram, 360
Mata Sánchez D., Muñoz-Darias T., Casares J., Corral-Santana J. M., Shahbaz T., 2015, MNRAS, 454, 2199
Matsuoka M. et al., 2009, PASJ, 61, 999
Monet D. G. et al., 2003, AJ, 125, 984
Muñoz-Darias T., Fender R. P., Motta S. E., Belloni T. M., 2014, MNRAS, 443, 3270
Natalucci L., Cornelisse R., Bazzano A., Cocchi M., Ubertini P., Heise J., in 't Zand J. J. M., Kuulkers E., 1999, ApJ, 523, L45
Natalucci L., Bazzano A., Cocchi M., Ubertini P., Heise J., Kuulkers E., in 't Zand J. J. M., Smith M. J. S., 2000, ApJ, 536, 891
Negoro H. et al., 2015, Astron. Telegram, 7504
Negoro H. et al., 2016, Astron. Telegram, 9565
Nelemans G., Jonker P. G., 2010, New Astron. Rev., 54, 87
O'Donoghue D. et al., 2006, MNRAS, 372, 151
Patruno A., Watts A. L., 2012, preprint (arXiv:1206.2727)
Patruno A., Altamirano D., Hessels J. W. T., Casella P., Wijnands R., van der Klis M., 2009, ApJ, 690, 1856
Patruno A., Altamirano D., Messenger C., 2010, MNRAS, 403, 1426
Plotkin R. M., Gallo E., Jonker P. G., 2013, ApJ, 773, 59
Rau A., Yates R., Greiner J., 2015, Astron. Telegram, 7524
Reig P., 2011, Ap&SS, 332, 1
Remillard R. A., McClintock J. E., 2006, ARA&A, 44, 49
Remillard R. A., Swank J., Strohmayer T., 2002, IAU Circ., 7893
Shaw A. W. et al., 2013, MNRAS, 433, 740
Sugimoto J. et al., 2015, Astron. Telegram, 8143
Tanaka K. et al., 2016, Astron. Telegram, 8529
van Dokkum P. G., 2001, PASP, 113, 1420
van Paradijs J., McClintock J. E., 1994, A&A, 290, 133
Vaughan B. A. et al., 1994, ApJ, 435, 362
Verner D., Ferland G., Korista K., Yakovlev D., 1996, ApJ, 465, 487
Watson D., 2011, A&A, 533, A16
Wijnands R., Wang Q. D., 2002, ApJ, 568, L93
Wijnands R., Rol E., Cackett E., Starling R. L. C., Remillard R. A., 2009, MNRAS, 393, 126
Wijnands R., Degenaar N., Armas Padilla M., Altamirano D., Cavecchi Y., Linares M., Bahramian A., Heinke C. O., 2015, MNRAS, 454, 1371
Willingale R., Starling R. L. C., Beardmore A. P., Tanvir N. R., O'Brien P. T., 2013, MNRAS, 431, 394
Wilms J., Allen A., McCray R., 2000, ApJ, 542, 914
Yan Z., Yu W., 2015, ApJ, 805, 87

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