The optical counterpart of the bright X-ray transient Swift J1745–26

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ABSTRACT
We present a 30-day monitoring campaign of the optical counterpart of the bright X-ray transient Swift J1745–26, starting only 19 min after the discovery of the source. We observe the system peaking at \( t \sim 17.6 \) on day six (MJD 561 92) to then decay at a rate of \( \sim 0.04 \) mag d\(^{-1}\). We show that the optical peak occurs at least 3 d later than the hard X-ray (15–50 keV) flux peak. Our measurements result in an outburst amplitude greater than 4.3 mag, which favours an orbital period \( \lesssim 21 \) h and a companion star with a spectral type later than \( \sim A0 \). Spectroscopic observations taken with the Gran Telescopio de Canarias 10.4 m telescope reveal a broad (full width at half-maximum \( \sim 1100 \) km s\(^{-1}\)), double-peaked Hα emission line from which we constrain the radial velocity semi-amplitude of the donor to be \( K_2 > 250 \) km s\(^{-1}\). The breadth of the line and the observed optical and X-ray fluxes suggest that Swift J1745–26 is a new black hole candidate located closer than \( \sim 7 \) kpc.

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

1 INTRODUCTION
Low mass X-ray binaries (LMXBs) are interacting binaries harbouring a neutron star (NS) or a black hole (BH) accreting from a companion star typically lighter than the Sun. Accretion takes place via an accretion disc, where gravitational energy is efficiently converted into radiation (Shakura & Sunyaev 1973). LMXBs are multiwavelength sources, emitting from high energies to radio through different thermal and non-thermal processes (e.g. Fender 2006; Remillard & McClintock 2006). If the mass-transfer rate is high enough, these systems are always bright, with X-ray luminosities in the range \( L_X \sim 10^{36}–39 \) erg s\(^{-1}\). They are so-called persistent sources, whereas LMXBs with lower mass-transfer rates tend to be found as X-ray binary transients (XRTs). These objects spend most part of their lives in a dim, quiescent state, displaying luminosities as low as \( L_X \sim 10^{31} \) erg s\(^{-1}\). However, with recurrence times of a few months to decades, they undergo periods of activity, becoming as bright as persistent systems. It is during these outbursts, typically lasting a few weeks to months, when they are discovered by X-ray telescopes and subsequently studied using multiwavelength facilities.

Active X-ray binaries display a well-known phenomenology at high energies (e.g. van der Klis 2006; Belloni, Motta & Muñoz-Darias 2011). They also show very distinctive optical features, such as broad double-peaked emission lines testifying to the presence
of an accretion disc (e.g. Charles & Coe 2006). Galactic BHs are mostly found as XRTs, whereas the vast majority of the persistent population harbour NSs. This is not well understood yet, but could be related to the dependence on the compact object mass of the critical mass-transfer rate for a system to be persistent (e.g. King, Kolb & Burderi 1996).

Swift J1745−26 (Swift J174510.8−262411; hereby J1745) was discovered by the Burst Alert Telescope (BAT; Barthelmy et al. 2005) onboard the Swift X-ray observatory on 2012 September 16 (Cummings et al. 2012a,b). Subsequent observations performed by Swift and INTEGRAL at X-ray wavelengths showed a significant flux increase during the following days together with X-ray properties resembling those typically seen in BH transients (e.g. Belloni et al. 2012; Sbarufatti et al. 2012; Tomsisck, Del Santo & Belloni 2012). Multiwavelength observations supported the X-ray binary nature of the system, although a definitive evidence for a BH accretor has not been reported yet (see de Ugarte Postigo et al. 2012; Rau et al. 2012; Russell et al. 2012 for optical/infrared; see also Corbel et al. 2012; Miller-Jones & Sivakoff 2012 for radio).

Here, we present the first study of the optical counterpart of J1745. It includes spectroscopic data and multiband photometric follow-up from a few minutes after its discovery until the source was no longer visible due to the Sun constraints. We compare the outburst evolution in the optical, with that at high energies (Swift/BAT 15–50 keV) and report the first constraints on some of the orbital parameters of the system.

2 OBSERVATIONS AND RESULTS

Our optical follow-up of J1745 began a mere 19 min after the Swift/BAT alert and continued for ~30 d. Five different facilities were utilized: (i) the 2 m Faulkes Telescope South (FTS; located at Siding Spring, Australia), (ii) OSIRIS attached to the Gran Telescopio de Canarias (GTC) 10.4 m telescope in La Palma (Spain), (iii) the 2.0 m Liverpool Telescope (LT) also in La Palma, (iv) the IAC80 82 cm telescope in Tenerife (Spain) and (v) the 2.2 m telescope at Calar Alto observatory (CAHA-2.2m) in Almeria (Spain). An observing log is presented in Table 1. Observations were taken mostly using the Sloan i′ filter, although V and R Johnson, J Bessel and Sloan u′, g′, r′, z′ bands were also used for some epochs. Bias and flat-field corrections were performed using IRAF routines and the flux of the optical counterpart was extracted and calibrated using three photometric comparison stars (Fig. 1). The error in our absolute calibration is ~0.1 mag. However, the relative errors between data points are much smaller, allowing us a detailed study of the outburst evolution. The i′ band light curve is presented in Fig. 2, for which we also used I-band data converted to i′ using the transformations of Jordi, Grebel & Ammon (2006). In total, our photometry covers the outburst evolution of J1745 with 19 visits.

The source is observed to brighten during the first ~6 d after the X-ray discovery at an average rate of ~0.1 mag d−1, peaking at i′ ~ 17.66 between days 5 and 10. Since day 10, a decay down to ~18.1 at a rate of ~0.04 mag d−1 is observed. We note that given the quiescence level (i′ > 23.1) reported by Hynes et al. (2012), we missed the major part of the outburst rise. Observations with filters other than i′ were also taken on a few occasions (Table 1). Our best V band determined magnitude is 20.0 ± 0.2 on MJD 561 91, the other two epochs having larger errors and being consistent with the earlier one. On MJD 562 04 using the CAHA-2.2 m, we measure g′ = 21.29 ± 0.12, r′ = 19.14 ± 0.04 and z′ = 16.82 ± 0.04, whereas the source was not detected in u′ (>21). The same day we observe the

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Figure 1. Finding chart of Swift J1745–26 in Sloan i′ band taken with the GTC-10.4 m telescope. The refined object coordinates (J2000) are 17:45:10.85 and −26:24:12.6, for which we estimate an absolute error of 0.3 arcsec. The three comparison stars used to carry out the flux calibration are labelled as A (i′=13.4), B (i′=13.2) and C (i′=16.2).

obtain i′ = 17.96 ± 0.03 and R = 18.45 ± 0.04 using the FTS. We observe the R−i′ colour to be 0.86 ± 0.09, 0.92 ± 0.08 and 0.97 ± 0.07 on days MJD 561 86, 561 91 and 561 95, respectively. Then, after the peak flux (and transition towards softer states; Belloni et al. 2012), it becomes bluer, being 0.80 ± 0.05 on MJD 562 04.

2.1 Spectroscopy

Four optical spectra were obtained on 2012 September 17 between 20:44:47 and 21:48:06 UT (i.e. only ~35 h after the discovery of the source) using the spectroscopic mode of OSIRIS/GTC. The system was at i′ ~ 18 mag at that time (see Fig. 2). Observations consisted of 2 × 900 s exposures using the R1000R grating, which
The optical counterpart of Swift J1745–26 covers the range from 5000 to 10 000 Å at a resolution power of $\lambda/\Delta \lambda \sim 1100$, followed by $2 \times 900$ s using the R1000B grating, with a wavelength coverage from 3600 to 7500 Å and a similar resolution. The slit was placed at the parallactic angle with a width of 1 arcsec. Unfortunately, observations were performed at a necessarily high airmass ($>2.0$) and hence high extinction. This considerably limited our analysis, which was effectively restricted to the 5000–7500 Å range covered in all the spectra. Data reduction was performed using standard IRAF procedures. No reliable flux calibration was possible due to the high airmass and variable conditions.

The spectrum is almost featureless in the 5000–7500 Å range (top panel in Fig. 3), except for the presence of a broad H$\alpha$ emission line, which is clearly detected in the four individual spectra (see bottom panel in Fig. 3). This feature, typically observed in compact binaries, has a double-peaked, asymmetric profile, as expected from an accretion disc origin (Smak 1969). The shape of the line, in particular the blue peak, is seen to vary from spectrum to spectrum along the ~1 h of our continuous monitoring (i.e. on time-scales of ~15 min). A Gaussian fit to the average H$\alpha$ profile gives an equivalent width of $\text{EW} = 12.6 \pm 0.5$ Å and full width at half-maximum of $\text{FWHM} = 1115 \pm 38$ km s$^{-1}$, whereas a peak-to-peak separation of $634 \pm 18$ km s$^{-1}$ is obtained by fitting the line with two Gaussians. These measurements are consistent with those found in other X-ray binaries and are discussed in Section 3. Finally, we note that the He $\lambda 6678$ emission line, typically seeing in X-ray binaries, is also detected in the average spectrum of J1745 (top panel in Fig. 3).

3 DISCUSSION

We have studied the evolution of the optical counterpart of the X-ray transient Swift J1745–26 using photometry and spectroscopy. The spectrum is dominated by a broad (FWHM $\sim 1100$ km s$^{-1}$), double-peaked H$\alpha$ emission. Since these lines are known to be naturally formed in geometrically thin accretion discs (Smak 1969; Horne & Marsh 1986), the detection confirms both the association of the proposed optical counterpart with the X-ray source and its X-ray binary nature. Indeed, H$\alpha$ is typically the most prominent optical emission line in X-ray binaries. Its EW can be as large as $\sim 100$ Å during the quiescence phase, becoming smaller ($\lesssim 20$ Å) during outburst. Therefore, our measurement (EW $\sim 13$ Å) is consistent with typical values observed during the earliest phases of the outburst (Fender, Homan & Belloni 2009).

Optical emission from active X-ray binaries arises in regions typically a few light seconds from the central object (see e.g. Hynes et al. 2006; Muñoz-Darias et al. 2007). This is mainly a result of X-ray reprocessing in the outer accretion disc (van Paradijs & McClintock 1994), but with some possible synchrotron jet contribution during hard X-ray states (Russell et al. 2006). Assuming that the H$\alpha$ emission originates in a Keplerian, outer disc rim, the broadness of its profile tells us about the projected velocity of the regions closer to its inner radius (see Horne & Marsh 1986). Therefore, it is expected to, at least, depend on (i) the mass of the compact object, (ii) the orbital inclination and (iii) the size of the accretion disc. Not surprisingly, the systems with broadest H$\alpha$ emission lines are found to be BHs with relatively high inclination e.g. XTE J1118+480 (FWHM $\sim 2500$ km s$^{-1}$; Torres et al. 2004). However, these measurements are taken in quiescence, where FWHM tends to be larger. For instance, in the BH binary GRS 1009–45 (Nova Vela 1993) FWHM $\sim 2000$ km s$^{-1}$ is measured during quiescence (Shahbaz et al. 1996; Filippenko et al. 1999) and FWHM $\sim 1370$ km s$^{-1}$ in outburst (della Valle & Benetti 1993). NS systems seem to follow the same trend, but displaying lower velocities. In quiescence, Cen X-4 (low inclination; Shahbaz, Naylor & Charles 1993) shows FWHM $\sim 640$ km s$^{-1}$ (Torres et al. 2002) and XTE J2123–058 (grazing eclipses; Zurita et al. 2000) displays FWHM $\sim 1300$ km s$^{-1}$ (Casares et al. 2002). For the latter, we estimate FWHM $\sim 500–600$ km s$^{-1}$ from the outburst spectrum shown in Hynes et al. (2001) and similar values have been observed in the eclipsing NS systems X1822–371 (Harlaftis, Charles & Horne 1997) and EXO 0748–676 (Pearson et al. 2006) also during active phases. In light of the above, the FWHM measured for J1745 fits better with a BH scenario. However, we note that the amount of measurements available is relatively low and that other orbital parameters like the orbital period (i.e. size of the disc) should play a role in this discussion.
3.1 Outburst evolution

The photometric follow-up presented here started very promptly after the Swift alert. However, in our first measurement the system had already brightened considerably from its quiescent level (Hynes et al. 2012). During the first ~6 d, it kept rising at a rate of 0.1 mag d\(^{-1}\) before peaking at \(i = 17.6\). This rate seems comparable with those seen in other XRTs. For instance, 0.36 mag d\(^{-1}\) was observed in XTE J1118+480 (Zurita et al. 2006), 0.14 mag d\(^{-1}\) in Aql X-1 (Shahbaz, Charles & King 1998) and ~0.25 mag d\(^{-1}\) in GRO J0422+32 (Castro-Tirado, Ortiz & Gallego 1997). After the peak, we see a decay at a rate of ~0.04 mag d\(^{-1}\) also comparable to the 0.05–0.07 mag d\(^{-1}\) rate reported in the aforementioned works. At the end of our 1-month monitoring, J1745 was still bright and far from quiescence.

In Fig. 2, we compare the optical and (15–50 keV) X-ray light curves directly. This clearly shows the X-ray peak occurring ~3 d before the optical. X-rays peaking before the optical emission is at odds with some observations of other XRTs, where the flux is seen to peak (and/or suggested to rise) earlier in the optical (e.g. Orosz et al. 1997; Shahbaz et al. 1998; Zurita et al. 2006). This is traditionally interpreted as a proof of an outburst propagation. However, we note that those works typically use softer bands (e.g. 2–10 keV) than that here (15–50 keV). If we consider the canonical outburst evolution (e.g. Belloni et al. 2011), soft X-rays will peak several days later than the BAT data. Indeed, preliminary work on this source by a part of our team shows that the maximum of the soft X-ray emission occurs around the same date or even later than the optical peak that we report in this work.\(^1\)

Adopting the spectral parameters reported by Tomsett et al. (2012), the peak X-ray flux corresponds to \(4.5 \times 10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\) in the 15–50 keV band (2.9 \times 10^{-8}\) erg cm\(^{-2}\) s\(^{-1}\) within 2–10 keV). This corresponds to ~1.2 Crab (2–10 keV), making J1745 one of the brightest XRTs in recent times. Assuming that the accretion rate does not exceed the Eddington limit, the maximum distance to the source is \(d \sim 7\) kpc for a BH and ~3 kpc for an NS.\(^2\) After the BAT peak, J1745 is observed to move towards softer X-ray states (Belloni et al. 2012). Since BHs undergo state transition at luminosities higher than 2 percent of the Eddington luminosity (Maccarone 2003), we estimate that \(1 \lesssim T_{\text{Edd}} \lesssim 7\) for a BH accretor. Using these constraints on the distance, we have over plotted the X-ray flux reported by Sbarufatti et al. (2012) together with our optical measurement (MJD 56186; i.e. hard X-ray state) in the optical–X-ray luminosity diagram presented by Russell et al. (2006) and Russell, Fender & Jonker (2007) for \(d = 1, 3\) and 7 kpc (Fig. 4). Here, we have used the column density (\(N_{\text{HI}} = 1.70 \pm 0.04 \times 10^{22}\) cm\(^{-2}\)) from Tomsett et al. (2012). We find that regardless of the distance assumed, J1745 is consistent with being a BH in the hard state. However, we note that smaller \(N_{\text{HI}}\) values will result in the system being consistent with a nearby (~1 kpc) NS LMXB.

3.2 Orbital parameters

The results presented here can be used to constrain the orbital parameters of J1745. The H\(\alpha\) peak-to-peak separation of 634 ± 18 km s\(^{-1}\) encodes information regarding the outer accretion disc velocity and was empirically related to the companion star projected velocity \((K_i)\) by Orosz et al. (1994). Defining the outer disc velocity \((v_{\text{d}})\) as half of the peak-to-peak separation (i.e. \(v_{\text{d}} = 317 \pm 9\) km s\(^{-1}\) for J1745), they find that \(v_{\text{d}}/K_i \sim 1.1–1.25\), which yields \(K_2 > 250\) km s\(^{-1}\) for J1745. We note that this value is a lower limit, since the Orosz et al. relation is obtained from quiescent accretion discs, which have larger \(v_{\text{d}}\) as a result of a smaller outer disc radius than in outburst (see Corral-Santana et al. 2013 for a discussion).

Our photometric data show a peak \(i\)-band magnitude of 17.6 corresponding to ~0.3 mJy. Assuming that the \(r'\sim i' \geq 1.2\) colour (MJD 562 04) is the same on MJD 561 95, we obtain an outburst amplitude in the SDSS-\(r\)-band \(\Delta r' > 4.3\) from the quiescent level reported by Hynes et al. (2012). Shahbaz & Kuulkers (1998) found a relation between the outburst amplitude in \(V\)-band \(\Delta V\) and the orbital period \((P_{\text{orb}})\). Using \(\Delta V = \Delta r'\) we obtain \(P_{\text{orb}} \lesssim 21\) h. The last assumption seems reasonable since during the outburst the optical spectrum (once corrected from extinction) is expected to be disc dominated and relatively flat (van Paradijs & McClintock 1994), whereas a strong contribution from a redder companion star is expected in quiescence. We note that in the case of \(\Delta V > \Delta r'\) the orbital period would be smaller. The Shahbaz & Kuulkers relation is valid for orbital periods \(P_{\text{orb}} \lesssim 1\) d, which seems consistent with the dim, quiescent optical counterpart. Periods longer than ~1 d would imply evolved companion stars with likely brighter quiescence levels (see e.g. King 1993; Muñoz-Darias, Casares & Martínez-Pais 2008). Using the relation reported in Faulkner, Flannery & Warner (1972), our constraint on the orbital period results in a mean density for the donor star >0.2 g cm\(^{-3}\). For a main-sequence companion, this limit yields a spectral type later than ~A0 (Cox 2000).

4 CONCLUSIONS

We have undertaken a detailed follow-up of the optical counterpart of the bright X-ray transient Swift J1745–26. All the observables suggest that Swift J1745–26 is a new BH candidate, as proposed by preliminary analysis of X-ray observations. We provide the first

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\(^1\) See http://www.rssd.esa.int/SD/INTEGRAL/images/POM2/2013-01.jpg

\(^2\) Here, we extrapolate the observed flux to the 0.1–100 keV band (~1.4 \times 10^{-7}\) erg cm\(^{-2}\) s\(^{-1}\)). We assume 1.4 M\(_{\odot}\) for an NS and the 8 M\(_{\odot}\) average mass for stellar mass BHs reported by Özel et al. (2010).
constraint on some of the fundamental parameters of this X-ray binary.

(i) The optical spectrum of J1745 shows a strong, double-peaked Hα emission line from which we infer a donor radial velocity semi-amplitude of $K_2 > 250 \text{ km s}^{-1}$. We also show that the breadth of this line (FWHM $\sim 1100 \text{ km s}^{-1}$) suggests a BH accretor.

(ii) Our photometric campaign revealed an outburst amplitude $>4.3 \text{ mag}$, favouring an orbital period lower than $\sim 21 \text{ h}$ and a companion star with a spectral type later than $\sim A0$.

(iii) The optical emission peaks at least 3 d after the hard X-rays. The observed optical and X-ray fluxes are consistent with J1745 being a BH in the hard state lying at a distance of $1 \lesssim \frac{d}{\text{TGC}} \lesssim 7$.

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