Black hole masses of tidal disruption event host galaxies II

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ABSTRACT

We present new medium resolution, optical long-slit spectra of a sample of six ultraviolet (UV)/optical and 17 X-ray-selected tidal disruption event candidate host galaxies. We measure emission line ratios from the optical spectra, finding that the large majority of hosts are quiescent galaxies, while those displaying emission lines are generally consistent with star formation dominated environments; only three sources show clear evidence of nuclear activity. We measure bulge velocity dispersions using absorption lines and infer host black hole (BH) masses using the $M-\sigma$ relation. While the optical and X-ray host BH masses are statistically consistent with coming from the same parent distribution, the optical host distribution has a visible peak near $M_{BH} \sim 10^6 M_\odot$, whereas the X-ray host distribution appears flat in $M_{BH}$. We find a subset of X-ray-selected candidates that are hosted in galaxies significantly less luminous ($M_g \sim -16$) and less massive (stellar mass $\sim 10^{8.5-9} M_\odot$) than those of optical events. Using statistical tests we find suggestive evidence that, in terms of BH mass, stellar mass, and absolute magnitude, the hard X-ray hosts differ from the UV/optical and soft X-ray samples. Similar to individual studies, we find that the size of the emission region for the soft X-ray sample is much smaller than the optical emission region, consistent with a compact accretion disc. We find that the typical Eddington ratio of the soft X-ray emission is $\sim 0.01$, as opposed to the optical events which have $L_{BB} \sim L_{Edd}$. The latter seems artificial if the radiation is produced by self-intersection shocks, and instead suggests a connection to the supermassive black hole.

Key words: accretion, accretion discs–galaxies: bulges–galaxies: fundamental parameters–galaxies: kinematics and dynamics–galaxies: nuclei.

1 INTRODUCTION

The study of tidal disruption events (TDEs), where stars are torn apart by the immense tidal forces near supermassive black holes (SMBHs) in the centres of galaxies, has emerged in recent years as a new tool to study both dormant and active SMBHs. Basic theoretical predictions (Hills 1975; Rees 1988; Evans & Kochanek 1989; Phinney 1989) were established two decades before the first observational claims of such events were made (Grupe et al. 1995; Grupe, Thomas & Leighly 1999). Observations across the electromagnetic spectrum have since led to candidate TDE detections at almost every wavelength, including hard X-rays (Bloom et al. 2011; Cenko et al. 2012; Hryniewicz & Walter...
2016), soft X-rays (e.g. Komossa & Bade 1999; Greiner et al. 2000), ultraviolet (UV)/optical (e.g. Gezari et al. 2008; van Velzen et al. 2011; Holoien et al. 2014; Arcavi et al. 2014), infrared (IR; van Velzen et al. 2016b; Jiang et al. 2016; Mattila et al. 2018), and radio waves (van Velzen et al. 2016a; Alexander et al. 2016). So far the majority of well-established TDEs have been identified in UV/optical surveys, and in addition three jetted TDEs have been classified in hard X-rays (Bloom et al. 2011; Cenko et al. 2012; Brown et al. 2015). The soft X-ray TDE candidates have remained somewhat more ambiguous because of the intrinsic X-ray variability observed in active galactic nuclei (AGNs), and an interpretation of these events as extreme AGN variability has not been completely ruled out (see e.g. Auchettl, Ramirez-Ruiz & Guillochon 2018, who show that ~1 per cent of AGN flares could resemble TDE emission). Another concern is the lack of temporal coverage and/or pre-flare X-ray limits that could rule out AGN activity. This leaves open the possibility that these flares are simply the extreme tail of normal AGN variability.

Although it is important to consider alternate explanations for large outbursts occurring in the centres of galaxies, such as accretion disc instabilities (Saxton, Perets & Baskin 2018), interacting supernovae (SNe; Drake et al. 2011; Dong et al. 2016; Saxton et al. 2018) or exotic stellar collisions (Metzger & Stone 2017), several lines of evidence have emerged to suggest that at least the UV/optical TDE candidates are due to the disruption of stars. These include (i) their temperature and blackbody radius evolution, which is unlike any known SNe (Hung et al. 2017; Holoien et al. 2018), (ii) their Eddington ratio and black hole (BH) mass distribution (Wevers et al. 2017; Mockler, Guillochon & Ramirez-Ruiz 2019), (iii) their luminosity function and volumetric rate as a function of BH mass (van Velzen 2018), (iv) their late-time UV emission, 5–10 yr after peak brightness (van Velzen et al. 2018b), and (v) their location in galaxies without significant emission line content, indicating no ongoing star formation nor AGN activity. For the X-ray selected candidates, Auchettl et al. (2018) studied the spectral and time evolution in comparison with an AGN sample and found that TDE candidates are significantly softer (see also e.g. Lin et al. 2011), less variable in terms of spectral hardness and display a more monotonic decay in their lightcurves.

Only a small fraction of UV/optical-selected TDEs were observed to be X-ray bright, and similarly, many X-ray-selected TDE candidates did not show contemporaneous UV/optical blackbody emission. For most of these events, however, this is explained by a lack of simultaneous observations and the true level of UV/optical emission is highly uncertain. Nevertheless, several objects have now been observed to be both optical and X-ray bright (e.g. ASASSN–14li, Holoien et al. 2016a; ASASSN–15oi, Holoien et al. 2016b; Gezari, Cenko & Arcavi 2017; PS18kh, Holoien et al. 2018; van Velzen et al. 2018a), suggesting that these flares all belong to the same class. The lack of X-ray emission in some UV/optical TDEs may be due to geometrical viewing angle effects, as in the AGN unification model (Metzger & Stone 2016; Dai et al. 2018). The specific orbital dynamics of the events has also been suggested as the potential origin of the observational dichotomy. For example, Dai, McKinney & Miller (2015) suggested that X-ray emission may arise from more relativistic (i.e. deeper penetrating) encounters, while UV/optical emission may dominate in less relativistic TDEs.

While the host galaxies of UV/optical-selected TDEs have been extensively studied (French, Arcavi & Zabludoff 2016, 2017; Hung et al. 2017; Law-Smith et al. 2017; Wevers et al. 2017; Graur et al. 2018), the host galaxies of soft X-ray TDE candidates have received comparatively little attention. Graur et al. (2018) studied a sample of 35 TDE candidates (including both UV/optical and X-ray-selected events) confirming the findings of Arcavi et al. (2014) and French et al. (2016) that, in the hosts of both TDE candidate classes there is an apparent over-representation of quiescent Balmer-strong (mQBS, post-starburst or E + A) galaxies. In addition, they conclude that the large-scale properties (such as the density at the effective radius) of the hosts could be good predictors for their sub-parsec scale properties. Interestingly, there exists a growing sample of optically discovered TDE candidates that were found in known AGN (e.g. Merloni et al. 2015; Blanchard et al. 2017). These events have well-studied host galaxies that were unambiguously identified as AGN based on their optical emission line content, whereas most of the X-ray-selected TDE candidates have not been studied in such detail. These discoveries raise the question of whether a sample of such events is being missed by current time-domain surveys due to selection biases against spectroscopic follow-up of variability in known AGN host galaxies.

A recent study of 53 000 galaxies in the Swift Burst Alert Telescope (BAT) archive by Hryniewicz & Walter (2016) led to the discovery of a sample of hard X-ray flares in otherwise X-ray quiescent host galaxies. Based on the time-scales and peak luminosities (of order 1044 erg s$^{-1}$) that results from the association of some of these flares with the unique host galaxy within the X-ray error circle, several are unlikely to be AGN flares or Galactic in nature; instead, these events have characteristics consistent with the expectations for TDE candidates. However, these events have received little further attention in the literature due to the lack of multiview wavelength data for both the flares and hosts. One important caveat to the TDE interpretation is the poor spatial resolution of the BAT instrument. The typical localization error circle is ~2 arcmin, so these events were assumed to be associated to the only host galaxy within this error circle, with several offsets between the best-fitting BAT position and the tentative host galaxy similar to the error circle size. On the other hand, given the low galaxy background density the probability of chance alignments is low, arguing in favour of the associations.

In this work, we present medium resolution spectroscopic observations of a sample of TDE candidates selected by UV/optical, soft X-ray, and hard X-ray observations. We aim to characterize the nature of the host galaxies of the X-ray selected events, to discriminate between the AGN flare and TDE interpretations, based on the emission line content (or lack thereof) in the optical spectra. We constrain the BH mass distribution with a total of 29 host galaxies (including both UV/optical and X-ray-selected hosts) and discuss physical implications for the TDE properties. We present the observations in Section 2, and discuss the velocity dispersion measurements in Section 3. The new results of our work, including emission line ratios, BH, and host galaxy masses are discussed in Section 4, and the implications of our measurements are explored in Section 5. Our conclusions are presented in Section 6.

2 OBSERVATIONS

We obtained medium resolution optical long-slit spectra to characterize the emission line content, and measure the velocity dispersions and infer BH masses for a sample of 17 X-ray-selected TDE candidate host galaxies (Table 1). For the candidate TDE RXJ1242, we were able to obtain a spectrum only for RXJ1242A, the brighter of the two potential host galaxies. Our results for this source rely on the (currently unverified) assumption that this is indeed the correct host galaxy. In addition, we present new observations of six UV/optical selected TDEs. We also include archival observations...
Table 1. Overview of the spectroscopic observations used in this work. We note the instrument used for the spectra, which is either WHT ISIS, Keck ESI, VLT X-shooter, CAHA PMAS/PPak V1200 or SDSS. Slit denotes the slit width, and $\sigma_{\text{inst}}$ is the velocity dispersion resolution at 4000 Å as measured from skylines or arc lamp frames.

We subtract the bias level, perform a flat-field correction and finally apply a wavelength calibration using CuNe + CuAr arc lamp frames in IRAF. Cosmic rays are removed using the lacos package in IRAF (van Dokkum, Bloom & Tewes 2012). We perform an optimal extraction of the spectra (Horne 1986) using an aperture with a size in the spatial direction equal to the slit width to obtain a spectrum of the central region of the galaxy. We also rebin the spectra to a linear dispersion on a logarithmic wavelength scale. From the associated arc lamp observations and/or sky emission lines, we measure the instrumental broadening, which is typically an FWHM (full width at half-maximum) resolution of $138 \pm 1$ km s$^{-1}$ at 4000 Å for a 1 arcsec slit and the blue R600 grating, but the actual value depends linearly on the slit width (see Table 1). This corresponds to a velocity dispersion of 59 km s$^{-1}$.

from the Sloan Digital Sky Survey (SDSS) for the sources RBS 1032, SDSS J1323, and RX J1420 (this event has two potential host galaxies, but we follow Graur et al. 2018 and assume RXJ1420A is the true host galaxy), and we use a measurement of the velocity dispersion from the Calar Alto Legacy Integral Field Area Survey survey (García-Benito et al. 2015) for NGC 6021. Finally, we measure the velocity dispersion for ASASSN–15lh from the X-shooter spectrum presented in Krühler et al. (2018). Below we briefly describe the instrumental setup of the new William Herschel Telescope (WHT) and Keck spectra and the data reduction process.

2.1 WHT/ISIS

Part of the observations were performed using the Intermediate dispersion Spectrograph and Imaging System (ISIS, Jorden 1990) mounted at the Cassegrain focus of the 4.2 m WHT situated on the Canary island of La Palma, Spain. Typically, we obtained spectra with the R600 gratings in both arms, in combination with the dichroic at 5300 Å. Some sources were observed with the R158R and R300B gratings. These latter are of too low spectral resolution to measure velocity dispersions below 400 km s$^{-1}$, but they do allow us to measure the emission line content. We ensured that the R600 grating observations were performed in slit-limited observing conditions, such that the instrumental resolution can be measured from sky emission lines or arc lamp observations if no sky lines are present. The spectra are presented in Fig. 1.

The data were reduced using the MAuna Kea Echelle Extraction (MAKEE) software package. The pipeline performs standard spectroscopic data reduction routines including a bias subtraction, a flat-field correction, and spectrum extraction. A spectrum of a
Figure 1. WHT/ISIS spectra of part of the sample of TDE hosts, in the host rest-frame. Top: the low-resolution spectra taken with the R300B and R158R gratings. Bottom: the R600 spectra. The latter spectra have been smoothed by a boxcar filter of width 3 pixels for display purposes. The solid lines indicate the wavelengths of the Balmer series transitions, while dotted–dashed lines show the Mg b triplet and dashed lines mark the Calcium H + K lines.

spectrophotometric standard star on the CCD was used to determine the trace of the science objects. The position of each echelle order is traced, optimally extracted and wavelength calibrated independently (using CuAr and HgNe + Xe arc lamp exposures), after which the orders are rebinned to a linear dispersion on a logarithmic wavelength scale with a constant dispersion of 11.5 km s\(^{-1}\) pixel\(^{-1}\) and combined using the combine command.

2.3 GTC/OSIRIS

Three sources were observed with the 10.4 m Gran Telescopio Canarios (GTC) located on La Palma, Spain using the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS, Cepa et al. 2000) instrument operated in long-slit spectroscopy mode. These data have been reduced using a custom PYTHON semi-automatic routine, based on IRAF and MOLLY\(^1\) tasks. The spectra are first bias subtracted and flat-field corrected. We use an optimal extraction with an aperture of 0.6 arcsec. Individual arc spectra are extracted from the 2D images at the position defined by the continuum trace of the science target. We measure an FWHM of 138 ± 2 km s\(^{-1}\) for the 0.6 arcsec slit width, corresponding to a velocity dispersion of 59 km s\(^{-1}\) at 4000 Å. To derive a precise wavelength calibration, we interpolate the results from arcs obtained before and after the observation; when not available, the nearest arc is selected. This wavelength calibration is further refined by comparing the sky emission line O I 5577.3 Å with its corresponding rest wavelength, from which we derive sub-pixel velocity drifts (<20 km s\(^{-1}\)) that are subsequently corrected. Finally, we remove the Earth velocity relative to the source at each observational epoch to obtain the final spectra in the solar system barycentre reference frame. The spectra are shown in Fig. 3.

All spectra are normalized to the continuum by fitting third-order cubic splines in MOLLY. We mask prominent absorption and emission lines during this process. Spectra for which multiple exposures were obtained are subsequently averaged by weighting

\(^1\)MOLLY is software developed by T. R. Marsh for the reduction and analysis of spectroscopic data.
Figure 2. Keck/ESI spectra of part of the sample of TDE hosts, in the host rest frame. The spectra have been smoothed by a boxcar filter of width 25 pixels for display purposes. There is a broad feature near 4500 Å (in the observed frame) that is caused by a detector artefact. The vertical lines are as in Fig. 1.

Figure 3. GTC/OSIRIS spectra of part of the sample of TDE hosts, in the host rest-frame. The spectra have been smoothed by a boxcar filter of width 5 pixels for display purposes. The vertical lines are as in Fig. 1.

Each exposure with its mean signal-to-noise ratio (S/N, variance). We provide the full observing logs, including dates and exposure times, in Table A2. The spectra can be made available upon request to the authors.

3 VELOCITY DISPERSION MEASUREMENTS

In this work, we use the Penalized Pixel Fitting (PPXF) routine (Cappellari 2017) in combination with the Elodie stellar template library (985 templates) to measure the stellar velocity dispersion using the absorption lines present in the spectra. We refer the reader to Wevers et al. (2017) for a detailed discussion of the method and caveats. Briefly, the set of 985 templates is compared to the galaxy spectrum, after which a limited number (typically 10–20) of templates is chosen to perform a detailed fit to the velocity (redshift) and line-of-sight velocity dispersion (LOSVD) of the spectrum. To this end, the templates are convolved with the LOSVD, which is parametrized by a series of Gauss–Hermite polynomials (up to fourth order), after which the best-fitting template is determined by $\chi^2$ minimization (see Cappellari 2017 for a detailed explanation of PPXF).
While we always aim to use only the central region of the galaxy spectrum (using, as outlined in Section 2.1, an extraction box with side equal to the slit width), some spectra have low S/N, leading to degeneracies in the fitting routine. In this case, we use instead an extraction region which covers the entire galaxy along the length of the slit in order to increase the S/N. During fitting, we mask the H Balmer lines (because they are known to be strongly Stark broadened), as well as emission lines of [O III] at $\lambda\lambda4959$, 5007, the diffuse interstellar band at 5780 Å and the Na i interstellar absorption lines at $\lambda\lambda5890$, 5895. We show an example fit to the spectrum of SDSS J0159 in Fig. 4, where the (smoothed) Keck spectrum is shown in black and the best-fitting template broadened to 124 km s$^{-1}$ is shown in red. The shaded regions are excluded during the fitting process. In some cases, the preliminary template fitting step which covers the entire galaxy spectrum has a higher SNR. Furthermore for three sources, PGC 1127938, PGC 1185375, and UGC 1791, the templates provide a poor fit to the overall galaxy spectrum but it is clear that the absorption lines are narrow. For these galaxies, we indeed measure very low velocity dispersion values ($\lesssim40$ km s$^{-1}$). Although the systematic errors may be larger than the statistical errors quoted in Table 2, we do not exclude these measurements as there is additional evidence that the BHs inhabiting these galaxies must be small ($\lesssim10^4 M_\odot$, see Section 4.4).

We use the measured velocity dispersions to infer the BH mass using the $M-\sigma$ relation presented in Ferrarese & Ford (2005). We remark that especially at the low end (velocity dispersions $\lesssim70$ km s$^{-1}$), it is unclear (both theoretically and observationally) whether galaxies should still follow the same scaling relations as derived for massive ellipticals (e.g. Graham 2008; Volonteri & Natarajan 2009; Xiao et al. 2011). Given that this debate is ongoing, we will assume for now that indeed the same scaling laws are applicable throughout the mass range considered here ($\sim10^5-10^8 M_\odot$).

4 RESULTS

In this section, we will first discuss new and potential mQBS (e.g. Graur et al. 2018) hosts, after which we analyse the emission line content of the galaxies, finding that the majority of both optical and X-ray host galaxies do not show evidence for significant emission lines. We end by presenting the BH mass distribution of all the galaxies in our sample, as well as galaxy stellar mass and bulge masses.
4.1 Quiescent Balmer strong galaxies

As first noted by Arcavi et al. (2014) for UV/optical selected TDEs, and later confirmed by French et al. (2016) and Graur et al. (2018), TDEs are found to be over-represented in quiescent, moderately Balmer strong galaxies (i.e. galaxies that experienced a recent starburst or have a truncated star formation history). We adopt the definition of Graur et al. (2018) based on the Lick absorption index that a moderately Balmer strong galaxy should have an HδA EW ≥ 1.3 Å in absorption, while the Hα EW should be less than 3 Å in emission. We find one source that satisfies these criteria. For the host galaxy LEDA 095953, we measure HδA EW = 1.8 Å and Hα EW = 1.9 Å in absorption. We estimate that the uncertainties on these measurements are ~0.5 Å. To obtain a lower limit on the Hα EW, we correct the measurement by 2.5 Å to estimate the EW corrected for stellar absorption. This is motivated by the finding of French et al. (2016) that the largest stellar absorption correction to the Hα EW for sources in their sample is ~2.5 Å. This yields Hα EW ≥ ~0.4 Å for the host LEDA 095953. In addition, we measure EW(HδA) = 3.5 Å for the host of DES14C1kia. Unfortunately, the H line is redshifted into the strong atmospheric absorption band near 7800 Å, making it difficult to gauge whether there is absorption or emission in the H line. We do not identify any narrow Balmer emission lines in the spectrum of DES14C1kia, nor any forbidden narrow emission lines, such as the Si or N doublets, nor O III at 5007 Å, that would indicate ongoing star formation or nuclear BH activity. This host galaxy could therefore be an additional member of the (m)QBS host galaxy population, although the lack of significant Hα emission would require a spectrum that does not suffer from atmospheric absorption bands to confirm.

Additionally, while remeasuring the Lick index for the source iPTF–16axa, we find a value of EW(HδA) = 4.1 Å, inconsistent with the measurement of Graur et al. (2018). Our measured value would result in a classification as mQBS rather than quiescent, even when adopting the same measurement uncertainty of 1.5 Å. This difference can potentially be attributed to the fact that in Graur et al. (2018), an extraction of the whole galaxy light along the slit was used to allow for a fair comparison to the wide fiber measurements from SDSS, whereas we repeated the measurement using the central extraction. Gradients in the HδA EW as a function of distance to the nucleus have been observed in other post starburst galaxies (Pracy et al. 2012). We therefore tentatively classify the host of iPTF–16axa as an mQBS galaxy.

4.2 Emission line ratios: BPT diagrams

The emission line ratios of forbidden nebular lines, such as [N II] λλ 6549, 6585, [S II] λλ 6317, 6331, and [O I] λλ 6301, in combination with Hα and Hβ have proven to be reliable indicators of the source of the ionizing radiation field in the nuclei of galaxies. In particular, we use the Baldwin–Phillips–Terwindt (BPT; Baldwin, Phillips & Terlevich 1981) diagram of the aforementioned line ratios measured from both the WHT and Keck spectra to investigate the most likely ionizing field. We note that the slit widths used probe different physical regions in the host galaxies due to their respective redshifts. We aim to identify potential AGN host galaxies using the three BPT diagrams (N/Si/O), although for some sources not all line ratios can be measured. We present measurements of the sources (where available) in three diagrams in Fig. 5. Different symbols indicate the nature of the TDE selection: circles for UV/optical (one source), stars for soft X-ray selected (three sources), and diamonds for the hard X-ray selected (three sources) candidates. The host galaxies of all the other TDE candidates do not show significant emission lines, indicating that they are probably quiescent (i.e. no observable star formation or nuclear activity).

NGC 6021 is unambiguously identified as an AGN based on its emission line content. Furthermore, the measured velocity dispersion of 187 km s⁻¹ translates to MBH = 1.2 × 10⁵ M☉, which is in excess of the Schwarzschild–Hills mass of a solar-type (or lower mass) star. Two other sources, namely PGC 015953 and SDSS J0139 (see also Merloni et al. 2015 and Section 4.5), are unambiguously identified as composite SF + AGN nuclei, while the rest is in the SF region of the diagrams. For 3XMM J1500, our GTC spectrum does not cover Hα, but Lin et al. (2017) report that it falls in the SF region. This disfavors AGN activity in the other host galaxies as the likely source for the variability.
in X-rays, with the notable caveat that for some sources our slit widths were wide (up to 1.5 arcsec), and nuclear star formation can potentially outshine the AGN (see e.g. Gezari et al. 2003). High spatial resolution spectroscopic observations are required to unambiguously determine the nuclear emission line content. Nevertheless, 19 out of 27 X-ray TDE host galaxies presented here do not have any observable emission line content, nor persistent X-ray emission (Auchettl et al. 2017; Hryniewicz & Walter 2016) making AGN activity an unlikely explanation for the majority of events.

4.3 Black hole masses

The BH mass distribution is presented in Fig. 6. We use a kernel density estimation to take into account the uncertainties in the velocity dispersion measurements as well as the scatter in the $M - \sigma$ relation. In particular, we use a Gaussian kernel with kernel width equal to the uncertainties in $M_{BH}$ quoted in Table 2 to represent each measurement as a probability density function (pdf). These pdfs are then summed over the relevant samples to obtain the distributions. We show the combined UV/optical (15 sources) + soft X-ray (11 sources) + hard X-ray (5 sources) mass distribution as a solid black line, while the red dashed, green dotted–dashed, and blue dotted lines represent the UV/optical, soft and hard X-ray selected sources, respectively. We regard ASASSN–14li and ASASSN–15oi as optical TDEs, as that is the wavelength domain they were discovered in. We reiterate that the sources at low $M_{BH}$ should be interpreted with caution due to the lack of calibration of the $M_{BH} - \sigma$ relation at these masses. On a side note, we confirm the discrepancy in BH mass for PS1–10jh from velocity dispersion measurements and light-curve modelling (Mockler et al. 2019).

Using the new GTC spectra, we measure $\sigma = 60 \pm 3$ km s$^{-1}$, consistent within the uncertainties with the value of $65 \pm 3$ km s$^{-1}$ reported in Wevers et al. (2017).
drawn from different parent populations. There is some marginal statistical evidence for the optical and soft X-ray samples being 0.12 (see also Table 3) for optical–soft X-ray, optical–hard X-ray, using the KCORRECT software (Blanton & Roweis 2007). If no SDSS stellar mass and absolute $g$-band magnitude of the host galaxies, we use SDSS photometry (where available) to calculate the total stellar mass and bulge masses from the same parent distribution. However, larger samples of sources are needed to robustly characterize differences in the mass distributions, in particular for the hard X-ray sample which consists of four sources. The results are presented in Table 2. The typical stellar mass content of the host galaxies, irrespective of the TDE selection criterion, is $10^{9.5} - 10^{10.5} M_\odot$ (see also Table 1 in van Velzen 2018). There are, however, several (both hard and soft) X-ray TDE hosts that are significantly less luminous and/or less massive (in terms of stellar mass) than the least massive and faintest optical TDE host (PS1–10jh, which has $M_g = -18.1$ and log($M_\star$) = 9.5 $M_\odot$). As for the BH masses, we perform KS and Anderson–Darling tests for the distributions of stellar mass and host absolute magnitude in the $g$ band, to reject the hypothesis that the different sample host (PS1–10jh, which has $M_g = -18.1$ and log($M_\star$) = 9.5 $M_\odot$). Absolute magnitudes of the host galaxies, with the null hypothesis that they are drawn from the same parent distribution. A $p$-value of 0.05 indicates that we can reject this hypothesis at the $2 \sigma$ level. The X-ray sample is the combination of the soft and hard X-ray sources.

We perform a two-sample Kolmogorov–Smirnov (KS) test to reject the null hypothesis that the mass distributions are drawn from the same parent distribution, and find that we cannot reject it at high significance. However, a KS test may not be the most appropriate test to use because the distributions of the different samples have similar mean values. The sample sizes are such that we do not expect significant biases in BH mass due to Poisson statistics, and there is no evidence for systematic biases against low- or high-mass SMBHs in the X-ray sample. From pairwise comparisons, we find a $p$-value of $p = 0.43$ for the optical and soft X-ray samples, $p = 0.30$ for the optical and hard X-ray samples, while for the soft and hard X-ray samples, we find $p = 0.33$ and finally for the optical and combined soft + hard X-ray samples we find $p = 0.36$. In other words, we cannot reject the null hypothesis that these distributions are drawn from the same parent distribution using the KS test.

As an alternative, we also use an Anderson–Darling test, which is more sensitive to the wings of the distribution for samples with similar values of the mean/mode. In this case, we find test statistics corresponding to $p$-values of $p = 0.28, 0.04, 0.06$ and 0.12 (see also Table 3) for optical–soft X-ray, optical–hard X-ray, soft–hard X-ray, and optical–X-ray, implying there is no robust statistical evidence for the optical and soft X-ray samples being drawn from different parent populations. There is some marginal evidence (at the $\sim 2\sigma$ level) that the hard X-ray sample is drawn from different parent distributions than the optical and soft X-ray samples. However, larger samples of sources are needed to robustly characterize differences in the mass distributions, in particular for the hard X-ray sample which consists of four sources.

4.4 Galaxy stellar masses and bulge masses

We use SDSS photometry (where available) to calculate the total stellar mass and absolute $g$-band magnitude of the host galaxies, using the KCORRECT software (Blanton & Roweis 2007). If no SDSS data are available, we use Pan-Starrs (PS1) data instead. We assume $H_0 = 0.7$ when fitting the photometry, and have corrected for Galactic dust extinction using the Schlegel, Finkbeiner & Davis (1998) dust maps. The results are presented in Table 2. The typical stellar mass content of the host galaxies, irrespective of the TDE selection criterion, is $10^{9.5} - 10^{10.5} M_\odot$ (see also Table 1 in van Velzen 2018).

In particular, there are three hard X-ray selected TDE candidate hosts, UGC 1791, PGC 1127938, and PGC 1185375, that have absolute magnitudes around $M_g = -16$ or fainter and are morphologically very similar to each other, lacking a clear bulge component. The latter two sources show no emission lines, whereas UGC 1791 is classified as an SF galaxy. Because the $M - \sigma$ relation is increasingly uncertain at the low velocity dispersions measured for these galaxies, we provide an alternative estimate using the relation between total stellar mass and BH mass (Reines & Volonteri 2015). This results in $M_{\text{BH}}$ in the range $\sim 10^{5.5} - 10^{6.5} M_\odot$ for these galaxies. To provide a more quantitative estimate of the central concentration, we use the bulge-to-total ($B/T$) $g$-band flux ratios (assuming a classical bulge) from Simard et al. (2011) for PGC1185375 (0.15) and PGC1127938 (0.40). For UGC1791, we estimate the ($B/T$) ratio in the $g$ band by taking the ratio of the PS1 PSF and Kron fluxes to estimate ($B/T$)$_g = 0.15$. Although a rigorous comparison is not possible with these estimates, it seems that while PGC1127938 is consistent with a higher than usual $B/T$ ratio seen in other TDE hosts, the other two sources have more typical low $B/T$ values as seen in SDSS galaxies at similar BH masses (fig. 5 in Law-Smith et al. 2017).

The hosts of two soft X-ray-selected events, 2MASX J0249 and RBS 1032, are less extreme outliers in terms of galaxy absolute magnitude and stellar mass when compared to the optical TDE hosts, although they are still fainter and less massive than the host of PS1–10jh (Fig. 7). These two galaxies are significantly more centrally concentrated; we estimate that for RBS1032, ($B/T$)$_g = 0.38^2$ and for 2MASX J0249, ($B/T$)$_g = 0.39$. Although it has been predicted that X-ray TDEs should preferentially occur around less massive SMBHs (which generally inhabit less massive and fainter galaxies; Dai et al. 2015), we find no clear systematic differences for the populations of soft X-ray and UV/optical selected TDEs as a whole in terms of galaxy luminosity or stellar mass (Table 2) nor BH mass. Instead, assuming that all events belong to the same parent population, there is a continuum in host galaxy properties, and our

\footnote{A ($B/T$)$_g = 0.75$ is reported in Law–Smith et al. (2017).}
optical spectroscopy of TDE host galaxies

We re-analyse the data presented by Esquej et al. (2007), obtained from the ING archive, and find that although the broad component is also visibly present in our reanalysis, given the low S/N, there is no statistical evidence of this component being real rather than noise. Given the significant amount of time (2 yr) between the flare detection in soft X-rays and the optical spectrum, it seems unlikely that this would be the optical spectroscopic signature of the TDE. On the other hand, this example does show how TDEs might masquerade in single-epoch spectroscopic surveys as ambiguous classifications of host galaxies with narrow emission lines, leading to a potential selection bias against finding such events in large spectroscopic surveys.

4.5.2 SDSS J0159

SDSS J0159 was identified by LaMassa et al. (2015) as a changing-look AGN, changing appearance in its optical spectrum with the broad Balmer lines disappearing as the X-ray luminosity and AGN continuum flux decreased by a factor of 6. These authors derive a BH mass based on the FWHM of the broad component of the Hβ line of $2 \times 10^8 M_\odot$. On the other hand, Merloni et al. (2015) argue that this event is consistent with a TDE based on the light-curve evolution and energetics. Here, we determine the velocity dispersion based on absorption features, which implies a BH mass of $\sim 10^{7.2} M_\odot$, significantly lower than the broad line estimate of LaMassa et al. (2015). This could suggest that the broad transient emission lines were the optical signature of a TDE, in which case no clear correlation between $M_{\text{BH}}$ and the emission line FWHM would be expected. The SDSS spectrum showing the broad Hα line was indeed taken near the peak of the optical light curve (Merloni et al. 2015). Fitting the narrow emission lines with Gaussian profiles yields a similar velocity dispersion measurement. However, with the relatively high resolution of our Keck spectrum, the narrow emission lines are clearly resolved into two narrower components. All emission lines are masked during the absorption line fitting, such that this does not affect the measured velocity dispersion. For the Hα emission line, we measure a peak-to-peak separation of $\sim 150 \text{ km s}^{-1}$; all emission lines show evidence for two kinematically distinct components. These two components could originate from the rotation of the narrow-line region (NLR), and were unresolved in all the spectra presented in LaMassa et al. (2015). Other explanations include galactic scale outflows (e.g. Greene et al. 2011) or merging galaxy pairs (where the two components originate from the NLR of each SMBH in a dual AGN system; e.g. Comerford et al. 2009).

5 DISCUSSION

5.1 A bias against AGN host galaxies?

The absence of TDEs in AGN host galaxies could be the result of a selection bias in the spectroscopic follow-up, but could potentially also be related to the dust content of AGNs (as compared to quiescent galaxies). The nuclear BHs in type 2 (narrow-line) AGN are by definition surrounded by a thick dusty structure obscuring the inner (broad line) region and SMBH, which would inhibit the detection of nuclear flares at UV/optical wavelengths. For type 1 AGN, intrinsic optical variability and the presence of persistent broad lines could inhibit the detection of the typical TDE signatures such as a fast rise
exponential decay lightcurve and transient broad ($\sim 10^4 \text{ km s}^{-1}$) H and He emission lines. The bias in the X-ray sample could also be partially ascribed to misclassification of variability in known AGNs. Nevertheless, given the close connection between galaxy mergers, the fuelling of the central BH in AGN, and star formation, it is expected that the TDE rate in these active galaxies should be comparable to or higher than in quiescent galaxies (e.g. Karas & Subr 2007; Kennedy et al. 2016). Although AGNs are relatively rare among the local galaxy population (accounting for about 5–10 per cent of the total number of galaxies, Kauffmann et al. 2003), mQBS galaxies are comparatively even rarer ($\sim 2$ per cent of the galaxy population). The BPT diagrams indicate that we are currently largely missing these events.

The observed over-representation of TDEs in rare E+A galaxies may connect to TDE rates in AGN, as the E + A evolutionary state is often reached following a period of intense star formation after a merger (Zabludoff et al. 1996). The post-merger evolution likely includes an AGN phase that expels the remaining gas and thereby quenches the star burst (Hopkins et al. 2006), after which unusual stellar dynamical processes can enhance the TDE rate. It is not yet clear which of the many proposed dynamical processes (Arcavi et al. 2014; Stone & Metzger 2016; Stone et al. 2018; Madigan et al. 2018) is predominantly responsible for elevating post-starburst TDE rates, but many of them are expected to arise prior to the cessation of star formation. Post-merger galaxies may therefore display similarly elevated TDE rates at all phases, including in the immediate progenitors of E + A galaxies, which include star-forming (SF, e.g. Tadhunter et al. 2017) and AGN hosts.

If the bias against TDEs in AGN is purely observational, a systematic and unbiased survey for TDE signatures in AGN host galaxies could help improve our understanding of the dynamical (or other) mechanisms that are responsible for the observed elevated TDE rate in E + A galaxies. Quantifying the TDE rate in terms of nuclear dust obscuration (e.g. $E(B-V)$ of the host galaxies) could show whether large scale gas/dust columns play a role in TDE observability.

5.2 Predictions for and correlations with black hole mass

Although accurate predictions for the BH mass distribution in the literature are scarce, some models do predict their preferred $M_{\text{BH}}$ distribution and/or correlations of other observables such as the temperature and peak luminosity with BH mass. We briefly explore these predictions here, starting with the BH mass distribution.

Dai et al. (2015) argue that thermal soft X-ray emission will only be produced around (i) low-mass SMBHs ($M_{\text{BH}} \lesssim 10^6 M_\odot$), where disc effective temperatures can reach into the X-rays, and (ii) in the case of a relativistic pericentre, which, for small SMBHs, implies a deeply plunging orbit. Although we cannot constrain the depth of disruption, the mass distribution of the soft X-ray sample, which is roughly flat in $M_{\text{BH}}$ up to $10^8 M_\odot$, seems incompatible with this prediction, perhaps indicating the presence of higher temperature discs due to large Kerr spin parameters and/or spectral hardening corrections. Alternatively, contamination of the X-ray sample by AGN could bias the distribution towards higher masses (but see Section 4.2).

At higher SMBH masses, all TDE pericentres are sufficiently relativistic to enable rapid circularization, unless stream crossings are impeded by Lense–Thirring precession (Guillochon & Ramirez-Ruiz 2015; Hayasaki, Stone & Loeb 2016). If high inner disc accretion rates are required to power UV/optical light curves (e.g. in reprocessing models such as Dai et al. 2018), one would then expect some bias towards higher mass SMBH hosts for UV/optical flares, although this bias is modest (e.g. fig. 11 in Stone & Metzger 2016). This also appears at odds with the current observations of both the UV/optical and X-ray sample (Fig. 6).

In terms of correlations between observables, if the UV/optical emission is produced in stream–stream collisions, Piran et al. (2015) predict that the temperature of the emission should scale inversely with $M_{\text{BH}}$ when streams self-intersect near apocentre, although a large spread in blackbody temperature will exist in a sample with varied penetration factors. We show the peak blackbody temperature as a function of BH mass in the top panel of Fig. 9, from which we conclude that no such inverse scaling is observed. The bottom panel of Fig. 9 shows the peak luminosity in the g band as a function of BH mass.

We overplot basic predictions of this model, assuming that a spherical photosphere at the self-intersection radius ($R_{\text{SI}}$) radiates a luminosity

$$L = \frac{M_{\text{dyn}} G M_{\text{BH}}}{R_{\text{SI}}} \quad (1)$$

where $M_{\text{dyn}}$ is the dynamical mass fall-back rate at peak and G the gravitational constant. This provides an upper limit for the shock-powered luminosity, as it assumes that all the stream kinetic energy is thermalized and radiated. This luminosity will be lower if (i) orbital plane precession from misaligned SMBH spin makes
the blackbody temperature and peak absolute magnitude in the We compute the integrated blackbody UV/optical emission using 5.3 Eddington ratio of the UV/optical and X-ray emission correctly predicts the UV/optical emission radius. with observations. predictions are required to investigate quantitative (dis)agreements consistent with the shock-powered model. More detailed model β stream when they self-intersect.

Figure 10. Eddington ratio of the early time UV/optical and X-ray emission observed in TDEs at peak. Black stars indicate the UV/optical emission, red triangles soft X-ray emission, blue circles hard X-ray emission, and orange diamonds UV late-time emission. No bolometric correction is applied for the X-ray measurements. The upward sloping lines indicate different Eddington ratios to guide the eye, while the dotted–dashed red line indicates the peak fall-back luminosity for a maximally spinning Kerr BH.

the stream self-intersections (Guillochon & Ramirez-Ruiz 2015; Hayasaki et al. 2016), (ii) some of the energy is converted into kinetic energy of material piling up at RS, and (iii) there is a strong surface density mismatch between the inbound and the outbound stream when they self-intersect.

The measurements in both temperature and luminosity are broadly consistent with low penetration factors, β ~1–2. As just explained, the luminosity from shocks in our simple model is likely a conservative upper limit, and depending on the details of the post-distruption dynamics may be significantly lower. In this respect, we note that if the luminosity is lower by as little as a factor of ~2, several events require β >2 in order to remain consistent with the shock-powered model. More detailed model predictions are required to investigate quantitative (dis)agreements with observations.

Finally, we will see in Section 5.4 that the shock model also correctly predicts the UV/optical emission radius.

5.3 Eddington ratio of the UV/optical and X-ray emission

We compute the integrated blackbody UV/optical emission using the blackbody temperature and peak absolute magnitude in the g band as in Wevers et al. (2017). The X-ray measurements are taken from Auchettl et al. (2017) and Hryniewicz & Walter (2016) for the soft and hard X-ray samples, respectively. No bolometric corrections are applied to the X-ray measurements. In Fig. 10, we plot the optical measurements as black stars, while the red triangles and blue circles represent the soft and hard X-ray-selected events, respectively. The late-time UV measurements from van Velzen et al. (2018b) are shown as orange diamonds. While the optical events tend to have Eddington ratios in excess of ~0.2L_Edd, the X-ray events appear to cluster at lower Eddington ratios, ranging from 10^{-4} to 0.05L_Edd. The average Eddington ratios of the optical and soft X-ray-selected events are 1 ± 1 and 0.27 ± 0.4, respectively (this does not include the two super-Eddington events Swift J1644 and Swift J2058, which are not considered in this work). For completeness we note that although the implied Eddington ratios for the three hard X-ray TDE candidates in dwarf galaxies are greater than 1, if we assume the BH mass estimates from the Reines & Volonteri (2015) relation (~10^{-8}M_⊙) to be more representative, their Eddington ratios are consistent with unity. It should be kept in mind that the X-ray light curves (and indeed, some of the light curves of the optical sample) are typically poorly sampled, and thus these estimates represent lower limits on the true peak luminosity.

Several soft X-ray-selected events clearly stand out from the rest of the soft X-ray sample near the Eddington limit of their host BHs: SDSS J1201, SDSS J1323, 3XMM J1500, and 3XMM J1521. SDSS J1201 and SDSS J1323 were identified in Auchettl et al. (2017) to have typical energy release times similar to the jetted events Swift J1644 and Swift J2058, while other aspects of the emission (such as the hardness ratio and power-law index) are similar to ASASSN–14li, which likely launched a mildly relativistic jet (Pasham & van Velzen 2018). While the Swift events had a highly super-Eddington plateau phase of X-ray emission, the fact that J1201 and J1323 are near the Eddington limit implies that the emission was not highly relativistic (hence the X-ray emission is thermal in nature), consistent with the findings of Auchettl et al. (2017) that the hardness ratios support thermal disc emission for these events. 3XMM J1500 was also identified by Lin et al. (2017) as a likely TDE with a 10 yr super-Eddington phase.

The peak UV/optical (blackbody) emission of TDEs is consistent with being Eddington limited (Fig. 10), and furthermore consistent with being produced in a region similar to the stream self-intersection radius, several hundreds of gravitational radii from the SMBH. Several suggestions as to the nature of the optical/UV emission exist, including the reprocessing of accretion power in a quasi-static debris layer (Loeb & Ulmer 1997; Guillochon, Manukian & Ramirez-Ruiz 2014; Coughlin & Begelman 2014; Roth et al. 2016), reprocessing in an outflow (Strubbe & Quataert 2009; Lodato & Rossi 2011; Miller 2015; Metzger & Stone 2016; Roth & Kasen 2018), and shock-powered emission from self-intersection debris streams (Piran et al. 2015; Shiokawa et al. 2015). In the first two frameworks, emission should naturally be capped near the Eddington limit, as is observed; such a limit does not exist a priori for shock-powered emission, but in practice, predicted luminosities in the shock-powered model are almost always sub-Eddington compared to the SMBH Eddington limit (Piran et al. 2015). We note, however, that the emission region of the UV/optical radiation is located 10–100 inner-most stable circular orbit (ISCO) radii from the SMBH (Fig. 11), and the local Eddington limit for radiation produced in situ at the self-intersection point is expected to be 10^3–10^4 times lower than the limit in the vicinity of the SMBH. This effectively makes the observed UV/optical emission highly super-Eddington if produced locally at the self-intersection point. The fact that the UV/optical emission appears to be capped at the SMBH Eddington limit seems to be artificial in the shock-powered scenario, which suggests that this is not the powering mechanism of this radiation component. The Eddington limited UV/optical emission instead suggests that the radiation is related to the SMBH.

ASASSN–15lh, a source whose nature is still debated (Dong et al. 2016; Leloudas et al. 2016; Margutti et al. 2017), is not an outlier when compared to other optical TDEs in terms of its Eddington ratio. If we use a simple dynamical prediction for the peak fall-back rate (e.g. Stone, Sari & Loeb 2013), and furthermore assume the
maximum radiative efficiency for a spinning BH (i.e. $\eta = 0.42$), we find that the emission of ASASSN–15lh is indeed consistent with the predicted Eddington ratio and luminosity (the red dotted–dashed line in Fig. 10).

Using the peak X-ray luminosity measurements from Auchettl et al. (2017), we can now calculate the Eddington ratios of the soft and hard X-ray-selected TDE candidates at the observed peak of the light curve and compare the results. We also include late-time UV measurements of a sample of 10 UV/optical discovered events presented in van Velzen et al. (2018b). From the latter measurements, these authors conclude that viscously spreading accretion discs are present at late times (5–10 yr after peak), with the emission inconsistent with a simple power-law decay extrapolated from the early light curve. This inconsistency with a simple power-law decay is also observed in the X-ray light curves (Auchettl et al. 2017). We apply a (model-independent) bolometric correction factors based on the ratio of the UV luminosity van Velzen et al. (2018b) and the integrated UV/optical luminosity. In Fig. 10, these are shown as orange diamonds; their Eddington ratios are similar to those of the X-ray observations, although for the latter no bolometric correction is applied.

If returning tidal debris (i) circularizes promptly and (ii) forms an unobscured accretion flow, then simple disc models predict thermal soft X-ray emission at Eddington or higher levels (Ulmer 1999; Lodato & Rossi 2011). The relatively low observed X-ray Eddington ratios, $L_X \sim 0.01 L_{\text{Edd}}$, suggest that one of these two assumptions is incorrect (it is unlikely that the true peak X-ray luminosities are one or two orders of magnitude higher due to the sparse temporal sampling, given the observed decay rates, Auchettl et al. 2017).

TDE discs assemble rapidly when streams have relativistic pericentres and are confined to a single orbital plane (Hayasaki, Stone & Loeb 2013; Bonnerot et al. 2016), but disc assembly can be delayed for non-relativistic pericentres or around spinning SMBHs (see Section 5.2). A more slowly assembled disc will see slower time evolution in its X-ray light curve, as is observed in most soft X-ray TDEs (Auchettl et al. 2017).

On the other hand, Mockler et al. (2019) showed that the optical events likely have short circularization and viscous time-scales, indicating that material falls back to the SMBH at super-Eddington rates after disruption. The question that needs to be addressed is, then, why do we not observe luminous X-ray radiation at early times. Dai et al. (2018) recently proposed a unified model for TDEs, where X-ray radiation is only visible when the observer is looking down the funnel of a jet or outflow (see also Metzger & Stone 2016). The relatively large spread in Eddington ratio ($10^{-4} - 1$) would then be the result of varying amounts of reprocessing and extinction due to variations in the covering fractions of optically thick material. This is consistent with the late-time X-ray detections of several optical TDEs (PTF–09axc, PS1–10jh, and D3–13; Auchettl et al. 2017), when the obscuring material has had time to disperse and become optically thin to the X-ray radiation. Combined X-ray and optical observations of a large sample of TDEs are necessary to test the
(early-time light curve) predictions of this model by quantifying the relative fractions of X-ray bright optically dim, optically bright X-ray dim, and X-ray bright optically bright events, respectively.

We now turn our attention to the physical regions in which the various emission components originate.

5.4 The emission region of the UV/optical and X-ray emission

Under the assumption of isotropic emission, Wevers et al. (2017) derive the blackbody radii of the emission regions responsible for the UV/optical early-time radiation, and compare them to some simple theoretical models, including the stream self-intersection radius and a compact accretion disc at $R \sim R_e$ (Phinney 1989), with $R_e$ the pericentre radius of the orbit of the disrupted star. We update their fig. 9 by including the rest of the optical sample considered in this work (Fig. 11). All the optical events cluster near regions of impact parameter $\beta \sim 1–2$ consistent with previous results, and in continued agreement with predictions for shock-powered optical emission (Piran et al. 2015).

Having studied soft X-ray TDE host galaxies in this work, we are now able to include the expected emission region of the soft X-ray component as well. We provide two different estimates, as follows. Our first approach is to take the peak luminosities from Auchettl et al. (2017), and assume a typical blackbody temperature of 75 eV (similar to ASASSN–14li, van Velzen et al. 2016a and ASASSN–15oi, Holoien et al. 2016b). We then assume that the X-rays are isotropic blackbody emission. This is unlikely to be correct for all X-ray sources, given that Auchettl et al. (2017) find several whose X-ray spectrum is better described by a power-law, and, moreover, there are no meaningful constraints on the spectral shape of the hard X-ray-selected events. Nevertheless, given that the constraints on the X-ray spectral shape are not generally very strong, taking this approach allows us to make a simple approximation of the likely X-ray emission region. We assume uncertainties of 50 percent on the peak luminosity of the hard X-ray events because of the sparse temporal sampling. As shown in Fig. 11 (red triangles), the typical emission radius we find is of order $10^{12}$ cm or lower (Table A1), 2–3 orders of magnitude smaller than the optical emission region.

As a more self-consistent approach, we refit the X-ray spectra from Auchettl et al. (2017) with a two-parameter blackbody model (we use TBBABS × ZASPECT × BBODYRAD as our model in XSPEC), regardless of whether this provides the best overall fit to the data. This allows us to derive the blackbody temperature and radius for each source individually. Good quality spectra are available for ASASSN–14li, ASASSN–15oi, 2MASX J0249, SDSS J1201, SDSS J0159, and RBS 1032 (Table A1). We show these measurements as purple diamonds in Fig. 11, and they occupy a similar parameter space as our other approximation for X-ray source size. In all cases, the X-ray emission regions are much more compact than the early-time optical emission regions. Our estimate of compact X-ray source size is consistent with individual object studies (van Velzen et al. 2016a; Holoien et al. 2016b).

Interestingly, the X-ray emission region estimates are also at least an order of magnitude smaller than the radii of the viscously spreading accretion discs inferred from late-time UV observations, and in many cases are smaller than plausible ISCO radii. An effective X-ray emitting area less than that of disc annuli near the ISCO can only be explained by a large degree of obscuration, which would lend support to the reprocessing paradigm. However, we must emphasize that these results are only suggestive, as there are many uncertainties in our X-ray source size calculations. In particular, the high reduced $\chi^2$ values suggest that a blackbody model does not describe the data very well. More detailed modelling as well as higher quality data will be needed to more accurately test whether the X-ray emitting areas are less than the effective ISCO area in TDEs.

We also overplot the measurements by van Velzen et al. (2018b) as orange diamonds; these discs have typical radii between $10^{13}$ and $10^{14}$ cm, significantly smaller than the early-time UV/optical emission but significantly larger than the inferred X-ray emission region. If we assume that the X-ray emission also has its origin as accretion disc emission, it is not surprising to find the X-ray emission region being more compact than the UV emission, given that the X-rays are likely produced in the hot inner part of the disc, while the UV is produced at its outermost annuli (Lodato & Rossi 2011).

6 CONCLUSIONS

We have analysed new and archival spectroscopic observations of 21 X-ray TDE host galaxies, as well as 17 UV/optical TDE hosts (we present new observations for six of these latter sources). We find that a majority of X-ray TDEs occurred in quiescent host galaxies, while of the hosts that show emission lines, only three have a clear AGN signature in a BPT diagram. This provides supporting evidence that the majority of these events are indeed due to the tidal disruptions of stars, and not due to accretion disc instabilities or alternative scenarios related to AGN activity. We further analysed the host galaxy properties, and conclude the following:

(i) We identify two new members of the quiescent moderately Balmer strong class of galaxies: iPTF–16axa (optical TDE) and LEDA 095953 (soft X-ray TDE). For a third candidate with strong H$\alpha$ absorption, DES14C1kia, the H$\alpha$ line is redshifted into an atmospheric band and we cannot verify the lack of H$\beta$ emission (although no other lines expected in SF galaxies are detected).

(ii) Three hard X-ray TDE candidates (out of a total sample size of six for this class) occurred in dwarf galaxies with $M_\star \sim 16$ and $M_\star \sim 10^{8.5–9}$, an order of magnitude fainter and less massive than the least massive optical TDE host. It is still unclear whether these events are truly TDEs. Two soft X-ray host galaxies fall in the gap between these two groups. Although the BH masses are uncertain, this further indicates that the rate of TDEs is dominated by low-mass BHs and host galaxies, as predicted by theory. If the hard X-ray events are indeed TDEs, we conclude that a non-zero fraction of dwarf galaxies at those masses host massive BHs. For these three galaxies, the BH mass derived from the velocity dispersion is $\sim 10^{4.5–5} M_\odot$; if instead we use the galaxy stellar mass, we find $M_\text{BH} \sim 10^{5.5} M_\odot$.

(iii) There is no robust statistical evidence that the TDE host SMBH masses, stellar masses, or absolute magnitudes are drawn from different parent distributions when one compares our UV/optical and soft X-ray-selected subsamples. For the hard X-ray sample, on the other hand, we can reject the hypothesis that its host properties are drawn from the same parent distribution as the optical and/or soft X-ray samples at the $\sim 2 \sigma$ level. The fact that this is the case for all three host properties we examine suggests that this difference is likely real, although a larger sample should be used to provide conclusive evidence.

(iv) The Eddington ratio of the observed TDE X-ray emission is typically of order 0.01 (with a large range $10^{-4}–1$), whereas for the optical emission it is typically of order 1. There is no correlation between $L_{\text{X-ray}}$ and $M_\text{BH}$, which might have been expected were AGN outbursts or unobscured accretion of rapidly circularizing
TDE debris the power source. Instead, the Eddington ratio of the X-ray emission is similar to that of late-time UV emission (van Velzen et al. 2018b). This implies that the accretion rate at the time of the X-ray observations is similar to the accretion rate at the time of the UV measurements (although potential obscuration and/or a bolometric correction are not yet taken into account).

(v) Estimates of the emission region of the X-ray radiation leads us to conclude that it is (as expected) close to the BH, and significantly closer-in than both the early and late-time UV/optical emission regions. The X-ray spectra suggest accretion disc emission, and a compact accretion disc model is certainly consistent with the observed Eddington ratios (the same is true for late-time UV emission). The size of the X-ray emitting region is more puzzling, however. While our simple fits for emitting area are subject to several uncertainties, if taken at face value, they indicate that many soft X-ray TDEs suffer from a high level of obscuration. Future work that more carefully examines uncertainties in the original X-ray spectrum could therefore usefully test the presence of reprocessing layers.

Many of our conclusions have been limited by the small size of the current TDE candidate sample. In the near future, this sample will expand by two orders of magnitude, as eROSITA and the Large Synoptic Survey Telescope (LSST) begin discovering thousands of new TDE candidates. This near-future sample will contain large amounts of information on the SMBH mass function, and in particular its low-end occupation fraction. However, such a large number of host galaxies may frustrate attempts to generalize the relatively expensive spectroscopic work of this study, highlighting the need for improved TDE light curve models that can infer SMBH masses through flare photometry alone.

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In this table, we give the relevant details of the blackbody model fitting of the X-ray spectra. Obs ID gives the observation identifier, MJD is the modified Julian date, $kT$ is the blackbody temperature, $bbnorm$ is the normalization constant of the blackbody spectrum, the radius is the physical radius of the emission region, $r$ is the reduced chi-square statistic of the fit, and d.o.f. gives the number of degrees of freedom.

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Table A2. In this table, we provide the observational setups, observing dates, and exposure times of the new optical long-slit spectra presented in this work. In addition, we also provide this information for the spectra presented in Wevers et al. (2017).

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<th>Exposure time (s)</th>
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