A Swift Fix for Nuclear Outbursts

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ABSTRACT

In November 2020, the Swift team announced an update to the UltraViolet and Optical Telescope calibration to correct for the loss of sensitivity over time. This correction affects observations in the three near ultraviolet (UV) filters, by up to 0.3 mag in some cases. As UV photometry is critical to characterizing tidal disruption events (TDEs) and other peculiar nuclear outbursts, we re-computed published Swift data for TDEs and other singular nuclear outbursts with Swift photometry in 2017 or later, as a service to the community. Using archival UV, optical, and infrared photometry we ran host SED fits for each host galaxy. From these, we computed synthetic host magnitudes and host-galaxy properties. We calculated host-subtracted magnitudes for each transient and computed blackbody fits. In addition to the nuclear outbursts, we include the ambiguous transient ATLAS18qqn (AT2018cow), which has been classified as a potential TDE on an intermediate mass black hole. Finally, with updated bolometric light curves, we recover the relationship of Hinkle et al. (2020), where more luminous TDEs decay more slowly than less luminous TDEs with decreased scatter as compared to the original relationship.

Keywords: Active galactic nuclei(16) — Black hole physics (159) — Near ultraviolet astronomy(1094) — Supermassive black holes (1663) — Tidal disruption (1696) — Transient sources (1851)

1. INTRODUCTION

A tidal disruption event (TDE) occurs when a star passes too close to a supermassive black hole (SMBH) and is torn apart by tidal forces. A fraction of the disrupted stellar material is subsequently accreted onto the SMBH, resulting in a short-lived, luminous flare (e.g., Lacy et al. 1982; Rees 1988; Evans & Kochanek 1989; Phinney 1989). Because they can occur in quiescent galaxies, TDEs are useful as probes of inactive black holes, and allow the study of accretion disks as they form, evolve, and are disrupted on observable timescales.

In recent years, wide-field, untargeted transient surveys, such as the All-Sky Automated Survey for Supernovae (ASAS-SN; Shappee et al. 2014; Kochanek et al. 2017), the Asteroid Terrestrial-Last-Impact Alert System (ATLAS; Tonry et al. 2018), the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS Chambers et al. 2016), and the Zwicky Transient Facility (ZTF; Bellm et al. 2019) have put substantial effort into identifying and studying transient outbursts thought to be TDEs. TDEs are identified as discrete flares nuclear flares with hot (1−5 × 10⁴ K) blackbody spectral energy distributions (SEDs) and broad hydrogen and/or helium lines in their optical spectra. Their temporal evolution is very different from the typical stochastic variability of AGN. In the process of searching for TDEs, other nuclear outbursts have also been discovered. Some may be unusual TDEs, such as TDEs occurring around existing
AGN (e.g., Blanchard et al. 2017; Payne et al. 2020), TDEs caused by an intermediate or stellar-mass black hole (e.g., Perley et al. 2019; Kremer et al. 2020), or unrelated phenomena like “rapid turn-on” and changing-look AGN (e.g., Shappee et al. 2014; Wyryzkowski et al. 2017; Frederick et al. 2019; Trakhtenbrot et al. 2019a).

A common feature of these nuclear outbursts is that a significant portion of their emission is emitted at ultraviolet (UV) wavelengths. As such, observations from space-based UV telescopes, in particular the Neil Gehrels Swift Observatory (Swift; Gehrels et al. 2004), are crucial for characterizing the temperatures and luminosities of these events. Nearly all transients identified as possible TDEs have thus been the subjects of extended monitoring campaigns with the Swift UltraViolet and Optical Telescope (UVOT; Roming et al. 2005).

In November 2020, the Swift team announced that due to a loss of sensitivity over time, the photometric calibration for the three UVOT UV filters needed to be retroactively corrected. This loss of sensitivity can affect UV observations made with Swift after 2017 by up to 0.3 magnitudes. Since Swift observations are often used to estimate blackbody temperatures in nuclear outbursts, a difference of 0.3 mag can have a significant effect on the estimated blackbody temperatures and luminosities, particularly for cases where the transient magnitude is close to that of its host galaxy. The UVOT photometry correction thus has the potential to affect not only the conclusions about individual objects, but also the conclusions of population studies (e.g., Arcavi et al. 2014; Hung et al. 2017; Hinkle et al. 2020; van Velzen et al. 2020).

Here we re-compute the Swift photometry for all previously published epochs of Swift data taken of TDEs and other singular nuclear outbursts that were observed by Swift in 2017 or later. This includes both transients discovered after 2017 and those discovered prior to 2017 that were still being observed after 2017. We have also used multi-wavelength archival data to model the SEDs of the transient host galaxies and produce host-subtracted light curves and blackbody models of these transients in a uniform way. We present the resulting corrected Swift light curves, host-subtracted light curves, and blackbody models, which we make publicly available.

In Section 2 we discuss the sample selection. Section 3 discusses the sources of archival photometry and the models for the SEDs of the transient host galaxies. Section 4 discusses our reduction of the Swift UVOT data and presents the raw and host-subtracted Swift light curves. Section 5 covers our blackbody models of the transient SEDs and presents the resulting luminosities, radii, and temperatures. Section 6 discusses our re-analysis of the peak-luminosity/decline-rate relationship we first presented in Hinkle et al. (2020). Finally, Section 7 summarizes the results of this work. Throughout this paper, we have used a cosmology with $H_0 = 69.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.29$, and $\Omega_{\Lambda} = 0.71$.

2. SAMPLE

For our re-analysis, we selected 35 objects that have been classified as TDE candidates or other nuclear outbursts in the literature. These objects are listed in Table 1, along with the references where the Swift photometry was originally published and the source classifications, typically either as an AGN or a TDE. Where the nature of a source is unclear, we list the classification as an “AGN/TDE”. All but one of our sources is consistent with the host nucleus. The lone exception, ATLAS18qmn (AT2018cow), is the brightest of the growing class of fast optical transients (e.g., Prentice et al. 2018; Ho et al. 2020; Coppejans et al. 2020). It has been interpreted as either an exotic supernova (e.g., Prentice et al. 2018; Perley et al. 2019), the tidal disruption of a star by an intermediate mass black hole (e.g., Perley et al. 2019; Uno & Maeda 2020), or the tidal disruption of a star by a stellar mass black hole in a star cluster (Kremer et al. 2020). We list it as “Ambiguous” in Table 1 and include it in our sample due to the potential TDE classification.

In our Swift re-analysis, we used a 5′′ radius aperture except for ASASSN-17cv, ASASSN-19dj, ZTF18aajupnt, ZTF19aaqmg, and ZTF19abzrhgq which used 10′′, 10′′, 10′′, 10′′, 10′′ radius apertures respectively. These larger apertures were chosen to incorporate the entire host galaxy. Additionally, the transient photometry for ATLAS18qmn was measured using a 3′′ radius aperture to minimize host contamination as the source is non-nuclear. We chose 5′′ as the default for sources without clear aperture sizes in the literature because 5′′ is the standard Swift aperture radius and has small aperture loss corrections (Poole et al. 2008).

3. HOST GALAXY SED FITS

In order to accurately measure the UV and optical photometry of each transient, we must first subtract the emission of the host galaxy. Two of our sources, ASASSN-19bt and ATLAS18qmn have Swift images of the host galaxy during quiescence (see Holoien et al. (2019a) and Perley et al. (2019) respectively), from

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1 https://www.swift.ac.uk/analysis/uvot/index.php
| Object            | TNS ID        | Right Ascension | Declination | Type            | References                                                                 |
|-------------------|---------------|-----------------|-------------|-----------------|----------------------------------------------------------------------------|
| ASASSN-14li       |               | 12:48:15.230    | +17:46:26.44| TDE             | Holoien et al. (2016a), Brown et al. (2017), van Velzen et al. (2019)       |
| ASASSN-15oi       |               | 20:39:09.183    | −30:45:20.10| TDE             | Holoien et al. (2016b), Gezari et al. (2017), Holoien et al. (2018)        |
| ASASSN-17cv       | AT2017bgt     | 16:11:05.696    | +02:34:05.52| AGN             | Trakhtenbrot et al. (2019a)                                               |
| ASASSN-18el       | AT2018saf     | 19:27:19.551    | +65:33:54.31| AGN/TDE         | Trakhtenbrot et al. (2019b), Ricci et al. (2020)                           |
| ASASSN-18jd       | AT2018cb      | 22:43:42.871    | −16:59:08.49| AGN             | Neustadt et al. (2020)                                                    |
| ASASSN-18pg       | AT2018dyb     | 16:10:58.774    | −60:55:23.16| TDE             | Leloudas et al. (2019), Holoien et al. (2020)                               |
| ASASSN-18ul       | AT2018fyx     | 22:50:16.090    | −44:51:53.50| TDE             | Wevers et al. (2019)                                                       |
| ASASSN-18uj       | AT2018hyz     | 10:06:50.871    | +01:41:34.08| TDE             | van Velzen et al. (2020), Hung et al. (2020a), Gomez et al. (2020)         |
| ASASSN-19bt       | AT2019ahk     | 07:00:11.546    | −66:02:24.14| TDE             | Holoien et al. (2019a)                                                    |
| ASASSN-19dj       | AT2019azh     | 08:13:16.945    | +22:38:54.03| TDE             | Liu et al. (2019), van Velzen et al. (2020), Hinkle et al. (2021)          |
| ATLAS18qgn        | AT2018cow     | 16:16:00.220    | +22:16:04.91| TDE             | Prentice et al. (2018), Perley et al. (2019)                               |
| ATLAS18way        | AT2018hco     | 01:07:33.635    | +23:28:34.28| TDE             | van Velzen et al. (2020)                                                   |
| ATLAS18yzs        | AT2018iih     | 17:28:03.930    | +30:41:31.42| TDE             | van Velzen et al. (2020)                                                   |
| ATLAS19qmu        | AT2019mha     | 16:16:27.799    | +56:25:56.29| TDE             | van Velzen et al. (2020)                                                   |
| Gaia19axp         | AT2019brs     | 14:27:46.400    | +29:30:38.27| AGN             | Frederick et al. (2020)                                                    |
| Gaia19bpt         | AT2019ehz     | 14:09:41.880    | +55:29:28.10| TDE             | van Velzen et al. (2020)                                                   |
| iPTF16fnl         | AT2016ezh     | 22:26:48.370    | +17:08:52.40| TDE             | Nicholl et al. (2019)                                                      |
| OGLE16aaa         |               | 01:07:20.880    | −64:16:20.70| TDE             | Wyrzykowski et al. (2017), Kajava et al. (2020)                             |
| OGLE17aaj         |               | 05:56:24.930    | −71:04:15.70| TDE             | Gromadzki et al. (2019)                                                    |
| PS16dtm           | AT2016ezx     | 01:58:04.739    | −00:52:21.74| TDE             | Blanchard et al. (2017)                                                    |
| PS17dhz           | AT2017eqx     | 22:26:48.370    | +17:08:52.40| TDE             | Nicholl et al. (2019)                                                      |
| PS18kh            | AT2018rze     | 07:56:54.537    | +34:15:43.61| TDE             | van Velzen et al. (2018)                                                   |
| ZTF18aahqkbdt     | AT2018bsi     | 08:15:26.621    | +45:35:31.95| TDE             | van Velzen et al. (2020)                                                   |
| ZTF18aaqumt       | AT2018dyk     | 15:33:08.015    | +44:32:08.20| LINER           | Frederick et al. (2019)                                                    |
| ZTF18actaqdw      | AT2018lni     | 04:09:37.652    | +73:53:41.66| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19aabbmzo      | AT2018lna     | 07:03:18.649    | +23:01:44.70| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19aaiqmglt     | AT2019avd     | 08:23:36.767    | +04:23:02.46| AGN             | Frederick et al. (2020)                                                    |
| ZTF19aakiwze      | AT2019cho     | 12:55:09.210    | +49:31:09.93| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19aakswrb      | AT2019hbf     | 15:09:15.975    | +16:14:22.52| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19aapreis      | AT2019dsq     | 20:57:02.974    | +14:12:15.86| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19aatubsej     | AT2019fdr     | 17:09:06.859    | +26:51:20.50| TDE             | Frederick et al. (2020)                                                    |
| ZTF19abhhjcc      | AT2019meg     | 18:45:16.180    | +44:26:19.21| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19abidbya      | AT2019wv       | 23:11:12.305    | −01:00:10.71| TDE             | van Velzen et al. (2020)                                                   |
| ZTF19abvgxqur     | AT2019pev     | 04:29:22.720    | +00:37:07.50| AGN             | Frederick et al. (2020)                                                    |
| ZTF19abzrhqz      | AT2019gqz     | 04:46:37.880    | −10:13:34.90| TDE             | van Velzen et al. (2020), Nicholl et al. (2020), Hung et al. (2020b)       |

Note—The 35 transients we re-analyze in this manuscript. TNS ID is the ID given for objects reported on the Transient Name Server. References include the discovery papers and papers using Swift data taken in 2017 or later. The type given reflects the classifications in the listed references. If using the revised photometry presented here, please cite both this paper and the original paper(s) in which Swift photometry was published.

a These sources have been interpreted as TDEs occurring in AGN host galaxies

which we directly obtained host fluxes. In the case of ATLAS18qgn, we measured the flux at the location of the transient, offset from the host galaxy nucleus. For most of our sources, there was no archival Swift coverage of the host galaxy. For these sources, we fit archival multi-wavelength photometry of the host galaxy using the Fitting and Assessment of Synthetic Templates code (FAST; Kriek et al. 2009) to obtain a spectral energy distribution (SED) of the host galaxy, from which we can estimate the UV flux.

For objects without Swift images in quiescence, we used published host galaxy magnitudes to fit the host galaxy SED with FAST when available. For sources
Table 2. Archival Host Photometry

| Object   | TNS ID    | Filter | Magnitude | Uncertainty |
|----------|-----------|--------|-----------|-------------|
| ASASSN-19dj | AT2019azh | NUV    | 18.71     | 0.05        |
| ASASSN-19dj | AT2019azh | u(SDSS) | 16.80     | 0.10        |
| ASASSN-19dj | AT2019azh | g(SDSS) | 15.12     | 0.04        |
| ASASSN-19dj | AT2019azh | r(SDSS) | 14.59     | 0.03        |
| ASASSN-19dj | AT2019azh | i(SDSS) | 14.35     | 0.03        |
| ASASSN-19dj | AT2019azh | z(SDSS) | 14.13     | 0.03        |
| ASASSN-19dj | AT2019azh | J      | 13.94     | 0.04        |
| ASASSN-19dj | AT2019azh | H      | 13.99     | 0.09        |
| ASASSN-19dj | AT2019azh | K_s    | 14.34     | 0.05        |
| ASASSN-19dj | AT2019azh | W1     | 15.07     | 0.03        |
| ASASSN-19dj | AT2019azh | W2     | 15.70     | 0.03        |

Note—Archival UV, optical, and infrared photometry used in the FAST SED fits for our objects. All magnitudes are presented in the AB system, using published conversions for systems naturally in the Vega system. For ASASSN-19bt and ATLAS18qq, the UVOT magnitudes listed were used to subtract the *Swift* photometry and the other photometry was used for the host SED fit. The TDE ASASSN-19dj is shown here to illustrate the format, while the full table is available as an ancillary file.

Without literature magnitudes we obtained *JHK_s* images from the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006) for near infrared (NIR) constraints and *ugriz* or *grizY* images from the from Sloan Digital Sky Survey (SDSS) Data Release 16 (Ahumada et al. 2020) or Pan-STARRS (Chambers et al. 2016) for optical constraints. We then measured aperture magnitudes of the host galaxy in the 2MASS and SDSS/Pan-STARRS data using the same aperture size as was used for the follow-up photometry (see Section 4), using nearby stars to calibrate the galaxy magnitudes. The TDEs ASASSN-19bt and OGLE16aaa were too far south to be observed by either SDSS or Pan-STARRS, so we obtained catalog magnitudes from the AAVSO Photometric All-Sky Survey (APASS; Henden et al. 2015) and the Dark Energy Survey (Abbott et al. 2018), respectively. We additionally obtained UV magnitudes from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005) All-sky Imaging Survey (AIS) catalog and W1 and W2 magnitudes from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) AllWISE catalog for all hosts in our sample. The archival photometry is shown in Table 2.

We then fit this archival host-galaxy photometry using FAST and assuming a Cardelli et al. (1988) extinction law with *R_V* = 3.1 and Galactic extinction at the coordinates of the host galaxy (Schlafly & Finkbeiner 2011), a Salpeter IMF (Salpeter 1955), an exponentially declining star-formation rate, and the Bruzual & Charlot (2003) stellar population models. We estimated the host flux in the UVOT filters for each FAST iteration by convolving the best-fit host SED from FAST with the filter response curve for each filter, obtained from the Spanish Virtual Observatory (SVO) Filter Profile Service (Rodrigo et al. 2012). In addition to the UVOT filters, we used the Bessel filter responses (Bessell 1990) to obtain Johnson-Cousins magnitudes. To estimate the uncertainties on the estimated host-galaxy fluxes, we performed a Monte Carlo sampling by perturbing the archival host fluxes assuming Gaussian errors and running 1000 different FAST iterations for each host galaxy. We took the median value as the magnitude and calculated 1σ errors by taking the difference between the 16th and 84th percentile values from the median and taking the larger value as the error. We then subtracted these synthetic host fluxes from the *Swift* photometry. In most cases, these synthetic magnitudes are well-constrained, but for host galaxies without GALEX magnitudes, such as the hosts of ASASSN-18pg, PS17dhz and ZTF19abidbya, the UV synthetic magnitudes often have large uncertainties as the star formation rates (SFRs), and thus UV emission, are poorly constrained. The synthetic magnitudes computed for each object, spanning from GALEX *FUV* to 2MASS *K_s* are shown in Table 3. In general, the archival and synthetic magnitudes agree within the uncertainties indicating a reasonable fit. For the objects with synthetic host magnitudes...
in the literature, such as PS18kh and ASASSN-18ul, our host values are largely consistent within the uncertainties. Any discrepancies are likely due to fitting different archival photometry and/or different choices made when fitting the host SEDs.

Because the TDE ASASSN-19bt (Holoien et al. 2019a) has Swift UVOT images with no transient source, we are able to test the accuracy of our synthetic Swift magnitudes. We fit GALEX NUV, APASS gri, 2MASS JHKs, WISE W1 and W2 photometry of the host galaxy, excluding the UVOT data, and then computed synthetic UVOT magnitudes. We find that for each of the six UVOT bands, the measured and synthetic photometry are consistent given the uncertainties. If we repeat this process without the GALEX NUV constraint, the differences are larger but the models are still consistent with the data given the larger uncertainties.

In addition to providing synthetic photometry for host flux subtraction, the FAST models constrain the age of the stellar population, the stellar mass, and the star formation rate of the host. Uncertainties on the host properties are computed in the same fashion as the synthetic magnitudes. In some cases our reported one-sided uncertainties are zero, which is a consequence of the grid spacing used in the FAST fitting procedure. In such cases, the median and either 16th or 84th percentile values are identical due to the discrete spacing of the grid in that parameter. This is most notable in the stellar population ages where the grid spacing was log(age) = 0.05. The SED fit to the host galaxy of ZTF19aabbnzo is particularly poorly constrained, with no limit on the SFR given the sampling. If we use the 99.7th percentile value, we obtain a weak upper limit of log[SFR (M⊙ yr⁻¹)] < −1.86.

Table 4 provides these host parameters for each of our host galaxies. FAST only fits stellar population synthesis models, so the fits for the galaxies known to host AGN have not taken into account a non-stellar component. Additionally for some of the larger galaxies, the default 5′′ radius used to match the Swift photometry does not encapsulate the full host galaxy. Finally, as expected, many of the TDE host galaxies are relatively low mass, consistent with hosting SMBHs less massive than ∼10⁷ M⊙ (van Velzen 2018; Wevers et al. 2019; Mockler et al. 2019).

4. Swift UVOT reductions

The UVOT has six typically used filters for photometric follow-up programs (Poole et al. 2008): V (5425.3 Å), B (4349.6 Å), U (3467.1 Å), UVW1 (2580.8 Å), UVM2 (2246.4 Å), and UVW2 (2054.6 Å). The wavelengths quoted here are the pivot wavelengths calculated by the SVO Filter Profile Service (Rodrigo et al. 2012), which we use throughout the remainder of this work.

Most epochs of UVOT data include multiple observations in each filter. We separately combined the images in each filter for each unique observation identification number using the HEASoft uvotimsum package. We then used the uvotsource package to extract source counts in a region centered on the position of the transient and background counts using a source-free region with radius of ∼30–40′. Our default source radius was 5′′ to minimize UVOT aperture corrections, but we matched the source radii used in the literature whenever possible, as described in Section 2. We then converted the UVOT count rates into fluxes and magnitudes using the most recent calibrations (Poole et al. 2008; Breeveld et al. 2010). For each UVOT image, we confirmed that the source did not lie on a region of the detector with known sensitivity issues3 (also see the Appendix of Edelson et al. 2015).

As the UVOT uses unique B and V filters, we converted the UVOT B and V data into the Johnson-Cousins system using color corrections4. For these filters, we used pivot wavelengths of V (5477.7 Å) and B (4371.1 Å), corresponding to the Bessel filter responses used in the synthetic magnitude calculations. Table 5 provides the Swift photometry in both magnitude and flux density without host subtraction or extinction correction.

After computing the raw Swift photometry, and correcting the BV data to the Johnson-Cousins system, we corrected each epoch of UVOT photometry for Galactic extinction (Schlafly & Finkbeiner 2011) (see Table 2) and removed the host contamination by subtracting the corresponding host flux in each filter. To compute the uncertainties, we added the uncertainty in the Swift photometry and the uncertainty in the host flux in that filter in quadrature. These results are provided in Table 6. Where the transient flux was less than a 3σ detection, we give a 3σ upper limit on the transient magnitude.

5. Blackbody fits

The host-subtracted UV/optical SEDs of TDEs (e.g., Holoien et al. 2014, 2016a) and some AGN flares (e.g., Neustadt et al. 2020) are well-fit as blackbodies. While in AGN the geometry of the emitting region is likely non-spherical and the emission is at least partly non-thermal, a simple blackbody fit should provide a reasonable estimate of the size and luminosity of the optically thick.

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3 https://swift.gsfc.nasa.gov/analysis/uvot_digest/sss_check.html
4 https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/swift/docs/uvot/caldb_coltrans_02b.pdf
Table 3. Synthetic Host-Galaxy Magnitudes

| Object       | TNS ID   | Filter       | Magnitude | Uncertainty |
|--------------|----------|--------------|-----------|-------------|
| ASASSN-19dj  | AT2019azh| FUV(GALEX)   | 20.449    | 0.863       |
| ASASSN-19dj  | AT2019azh| NUV(GALEX)   | 18.768    | 0.125       |
| ASASSN-19dj  | AT2019azh| UVW2(UVOT)   | 19.320    | 0.238       |
| ASASSN-19dj  | AT2019azh| UVM2(UVOT)   | 18.827    | 0.127       |
| ASASSN-19dj  | AT2019azh| UBVW1(UVOT)  | 18.196    | 0.108       |
| ASASSN-19dj  | AT2019azh| U(UVOT)      | 16.721    | 0.048       |
| ASASSN-19dj  | AT2019azh| B(UVOT)      | 15.445    | 0.079       |
| ASASSN-19dj  | AT2019azh| V(UVOT)      | 14.884    | 0.040       |
| ASASSN-19dj  | AT2019azh| U(J-C)       | 16.574    | 0.055       |
| ASASSN-19dj  | AT2019azh| B(J-C)       | 15.439    | 0.076       |
| ASASSN-19dj  | AT2019azh| V(J-C)       | 14.830    | 0.039       |
| ASASSN-19dj  | AT2019azh| R(J-C)       | 14.580    | 0.022       |
| ASASSN-19dj  | AT2019azh| I(J-C)       | 14.331    | 0.022       |
| ASASSN-19dj  | AT2019azh| u(SDSS)      | 16.623    | 0.049       |
| ASASSN-19dj  | AT2019azh| g(SDSS)      | 15.203    | 0.064       |
| ASASSN-19dj  | AT2019azh| r(SDSS)      | 14.630    | 0.026       |
| ASASSN-19dj  | AT2019azh| i(SDSS)      | 14.405    | 0.019       |
| ASASSN-19dj  | AT2019azh| z(SDSS)      | 14.211    | 0.029       |
| ASASSN-19dj  | AT2019azh| J(2MASS)     | 13.995    | 0.041       |
| ASASSN-19dj  | AT2019azh| H(2MASS)     | 13.798    | 0.050       |
| ASASSN-19dj  | AT2019azh| K_s(2MASS)   | 13.989    | 0.049       |

Note.—Synthetic host photometry computed from the Monte Carlo sampling of host galaxy SED fits with FAST. We used the Bessel filter responses (Bessell 1990) for our Johnson-Cousins synthetic magnitude calculations. All magnitudes are presented in the AB system, using published conversions for systems naturally in the Vega system. Note that the synthetic photometry listed in this table for ATLAS18qqn represents the entire host galaxy, not the region where the transient occurred and thus the UVOT magnitudes are significantly brighter. The values used for the subtraction of ATLAS18qqn are measured at the region of the transient from Swift images. The TDE ASASSN-19dj is shown here to illustrate the format and the full table is available as an ancillary file.

continuum-emitting region. Therefore, we include blackbody fits for each of the objects in our sample for completeness. For each epoch of host-subtracted UV photometry, we used Markov Chain Monte Carlo (MCMC) methods to fit a blackbody model, as used in Holoien et al. (2014, 2016a). The date listed for each epoch is the mean MJD of the data used in the fit. Unlike our 3σ detection limit for our reported Swift magnitudes, we employ a more liberal 2σ detection threshold for our blackbody fits as the models are fit in flux space and this allows for marginal detections of the transient at late times. We do not include blackbody fits for the TDEs ZTF18actaqdw, ZTF19aabbnzo, and ZTF19aakiwze, as their Swift light curves only have coverage in a single filter and we cannot constrain the temperature.

The Swift UVOT calibration correction only affected the UV filters, making them fainter than previously measured. This caused most objects to become cooler and therefore ∼15% - 30% less luminous than estimated from earlier reductions of Swift data. The evolution of blackbody parameters for the TDEs in this sample are shown in Figure 1. Even with corrections to the Swift UV data, all of the TDEs are hot, with temperatures of ∼15,000 – 50,000 K. The temperatures are roughly constant with time, although some objects show trends in their temperatures, both consistent with previous results (e.g., Hinkle et al. 2020; van Velzen et al. 2020). As noted in Hinkle et al. (2020), the more luminous TDEs appear to decay more slowly than their less luminous counterparts (see top panel of Figure 1).

Figure 2 shows the blackbody fits for the other nuclear outbursts. The luminosity range of these objects is much larger than for the TDEs because they span several source classes. The blackbody temperatures are still hot, consistent with the lower temperature range of TDEs. For many objects, the evolution in luminosity, radius, and temperature is much slower than for the TDEs, potentially due to these AGN hosting more massive SMBHs than the TDE hosts, although there is significant scatter in the various estimates of SMBH mass.
Note—Host-galaxy properties computed from the FAST SED models in addition to the host-galaxy redshift and Galactic visual extinction (Schlafly & Finkbeiner 2011). It is important to note that the radii used to measure the host photometry were chosen to match the Swift aperture radius and therefore for some objects do not encompass the entire host galaxy.

for some of these sources (e.g., Frederick et al. 2020). Additionally, unlike the TDEs, there seems to be no trend between peak luminosity and decline rate, consistent with the analysis of comparison objects in Hinkle et al. (2020).

6. PEAK-LUMINOSITY/DECLINE-RATE RELATIONSHIP

In Figure 1, the most luminous TDEs appear to have flatter slopes near peak, and decay more slowly than the less luminous TDEs, consistent with the relationship presented in (Hinkle et al. 2020). Given the importance of UV photometry to the bolometric UV/optical lightcurves on which this relationship is based, we reanalyzed this relationship with our updated Swift data. Similar to Hinkle et al. (2020), we have bolometrically corrected epochs without Swift UV data using nearby Swift epochs. Because the process of bolometrically correcting ground-based data involves heterogeneous data, we do not include the results of these bolometric correc-
Table 5. Unsubtracted Swift Photometry

| Object TNS ID  | MJD    | Filter | Magnitude | Uncertainty | Flux Density | Uncertainty |
|----------------|--------|--------|-----------|-------------|--------------|-------------|
| ASASSN-19dj AT2019azh | 58544.762 | V | 14.50 | 0.03 | 5.83E-15 | 1.77E-15 |
| ASASSN-19dj AT2019azh | 58553.457  | V  | 14.46 | 0.04  | 6.10E-15 | 0.24E-15 |
| ASASSN-19dj AT2019azh | 58544.758 | B  | 14.68 | 0.04  | 7.71E-15 | 0.32E-15 |
| ASASSN-19dj AT2019azh | 58553.454 | B  | 14.53 | 0.04  | 8.85E-15 | 0.37E-15 |
| ASASSN-19dj AT2019azh | 58544.757 | U  | 15.00 | 0.03  | 9.04E-15 | 0.25E-15 |
| ASASSN-19dj AT2019azh | 58553.453 | U  | 14.88 | 0.04  | 1.01E-14 | 0.04E-14 |
| ASASSN-19dj AT2019azh | 58544.755 | UVW1 | 15.00 | 0.04  | 1.63E-14 | 0.06E-14 |
| ASASSN-19dj AT2019azh | 58553.451 | UVW1 | 14.92 | 0.04  | 1.76E-14 | 0.06E-14 |
| ASASSN-19dj AT2019azh | 58544.763 | UVM2 | 14.92 | 0.04  | 2.32E-14 | 0.06E-14 |
| ASASSN-19dj AT2019azh | 58553.458 | UVM2 | 14.88 | 0.04  | 2.41E-14 | 0.09E-14 |
| ASASSN-19dj AT2019azh | 58544.759 | UVW2 | 14.75 | 0.04  | 3.24E-14 | 0.12E-14 |
| ASASSN-19dj AT2019azh | 58553.454 | UVW2 | 14.67 | 0.04  | 3.49E-14 | 0.13E-14 |

Note—Swift photometry of the transients without the host flux subtracted and with no correction for Galactic extinction. The BV photometry has been converted to the Johnson-Cousins system using the color-corrections described in the text. All magnitudes are presented in the AB system, using published conversions for systems naturally in the Vega system. The data for each source are grouped by filter and sorted by increasing MJD. The TDE ASASSN-19dj is shown here to illustrate the format and the full table is available as an ancillary file.

7. SUMMARY

Following the November 2020 announcement of an updated UVOT calibration to correct for the loss of sensitivity over time, we re-analyzed the published photometry for 34 nuclear outbursts and the ambiguous
### Table 6. Host-Subtracted Swift Photometry

| Object   | TNS ID    | MJD    | Filter | Magnitude | Uncertainty | Flux Density | Uncertainty |
|----------|-----------|--------|--------|-----------|-------------|--------------|-------------|
| ASASSN-19dj | AT2019azh | 58544.762 | V      | 15.85     | 0.17        | 1.66E-15     | 0.26E-15    |
| ASASSN-19dj | AT2019azh | 58553.457 | V      | 15.67     | 0.17        | 1.95E-15     | 0.31E-15    |
| ASASSN-19dj | AT2019azh | 58544.758 | B      | 15.27     | 0.12        | 4.46E-15     | 0.48E-15    |
| ASASSN-19dj | AT2019azh | 58553.454 | B      | 14.98     | 0.10        | 5.77E-15     | 0.52E-15    |
| ASASSN-19dj | AT2019azh | 58544.757 | U      | 15.05     | 0.04        | 8.61E-15     | 0.31E-15    |
| ASASSN-19dj | AT2019azh | 58553.453 | U      | 14.90     | 0.05        | 9.87E-15     | 0.45E-15    |
| ASASSN-19dj | AT2019azh | 58544.755 | UVW1   | 14.79     | 0.04        | 1.98E-14     | 0.08E-14    |
| ASASSN-19dj | AT2019azh | 58553.451 | UVW1   | 14.71     | 0.04        | 2.13E-14     | 0.08E-14    |
| ASASSN-19dj | AT2019azh | 58544.763 | UVM2   | 14.58     | 0.04        | 3.17E-14     | 0.12E-14    |
| ASASSN-19dj | AT2019azh | 58553.458 | UVM2   | 14.54     | 0.04        | 3.30E-14     | 0.13E-14    |
| ASASSN-19dj | AT2019azh | 58544.759 | UVW2   | 14.40     | 0.04        | 4.48E-14     | 0.17E-14    |
| ASASSN-19dj | AT2019azh | 58553.454 | UVW2   | 14.32     | 0.04        | 4.83E-14     | 0.18E-14    |

Note—Swift photometry of the transients with the host flux subtracted corrected for Galactic extinction. The uncertainties incorporate both the error on the photometry and from the host SED fits. For epochs where the transient flux was less than a 3σ detection, the magnitude column shows a 3σ upper limit on the transient magnitude. All magnitudes are presented in the AB system, using published conversions for systems naturally in the Vega system. The data for each source are grouped by filter and sorted by increasing MJD. The TDE ASASSN-19dj is shown here to illustrate the format and the full table is available as an ancillary file.

### Table 7. Blackbody Fits

| Object   | TNS ID    | MJD    | log(L)  | dlog(L)  | dlog(L_u) | log(R)  | dlog(R)  | dlog(R_u) | log(T)  | dlog(T)  | dlog(T_u) |
|----------|-----------|--------|---------|----------|-----------|---------|----------|-----------|---------|----------|-----------|
| ASASSN-19dj | AT2019azh | 58544.76 | 44.45   | 0.07     | 0.08      | 14.64   | 0.04     | 0.04      | 4.58    | 0.03     | 0.04      |
| ASASSN-19dj | AT2019azh | 58553.45 | 44.36   | 0.06     | 0.07      | 14.72   | 0.04     | 0.04      | 4.52    | 0.03     | 0.04      |
| ASASSN-19dj | AT2019azh | 58556.11 | 44.41   | 0.05     | 0.06      | 14.77   | 0.04     | 0.03      | 4.50    | 0.03     | 0.03      |
| ASASSN-19dj | AT2019azh | 58562.95 | 44.28   | 0.04     | 0.04      | 14.83   | 0.03     | 0.03      | 4.44    | 0.02     | 0.02      |
| ASASSN-19dj | AT2019azh | 58565.94 | 44.32   | 0.04     | 0.05      | 14.79   | 0.03     | 0.03      | 4.47    | 0.02     | 0.03      |
| ASASSN-19dj | AT2019azh | 58568.23 | 44.21   | 0.03     | 0.03      | 14.82   | 0.02     | 0.02      | 4.43    | 0.02     | 0.02      |
| ASASSN-19dj | AT2019azh | 58574.79 | 44.24   | 0.04     | 0.04      | 14.80   | 0.03     | 0.03      | 4.44    | 0.02     | 0.02      |
| ASASSN-19dj | AT2019azh | 58577.10 | 44.24   | 0.04     | 0.04      | 14.79   | 0.03     | 0.02      | 4.45    | 0.02     | 0.02      |
| ASASSN-19dj | AT2019azh | 58580.62 | 44.25   | 0.04     | 0.05      | 14.75   | 0.03     | 0.03      | 4.47    | 0.02     | 0.03      |

Note—Bolometric luminosity, effective radius, and temperature estimated from the blackbody fits to the host-subtracted and extinction-corrected Swift data. The TDE ASASSN-19dj is shown here to illustrate the format and the full table is available as an ancillary file.
Figure 1. Evolution of the UV/optical blackbody luminosity (top panel), effective radius (middle panel), and temperature (bottom panel) for the TDEs analyzed in this work. The shading corresponds to the uncertainty. Time is in observer-frame days relative to the earliest Swift epoch. We have not shown the very-late time ASASSN-14li blackbody properties, which are included in Table 7, to allow the evolution of the other TDEs to be seen more clearly.
Figure 2. Evolution of the UV/optical blackbody luminosity (top panel), effective radius (middle panel), and temperature (bottom panel) for the non-TDE transients or sources interpreted as TDEs in AGN host galaxies. The shading corresponds to the uncertainty. Time is in observer-frame days relative to the earliest Swift epoch.

source ATLAS18qqn. Starting from UVOT images, we re-computed Swift photometry, uniformly modeled the host galaxy SEDs with FAST, corrected the transient photometry for host flux and Galactic extinction, and fit the data with blackbody models. We provide tables of the raw and corrected Swift photometry of the transient, the observed and modeled host-galaxy photometry, the host-galaxy model parameters, and the blackbody models of the transients.

With our updated bolometric UV/optical light curves, we verify the relationship found by Hinkle et al. (2020), that more luminous TDEs decay more slowly than less luminous TDEs. With our uniform data analysis, the scatter in the relationship is significantly reduced.

Given the increased detection rate of TDEs and other exotic transients in recent years, the UV remains a vital wavelength range for studying the transient universe. In particular, UV photometry is a powerful tool for probing the regions close to SMBHs as sources evolve. As
Figure 3. Peak bolometric UV/optical luminosity as compared to the decline rate $\Delta L_{40} = \log_{10}(L_{40}/L_{\text{peak}})$, where $L_{40}$ is the luminosity of the TDE at 40 days after peak. The colors are the same as Hinkle et al. (2020) for ease of direct comparison. Following Hinkle et al. (2020), the filled squares with a black border are the “A” sample, filled circles with a black border are the “B” TDEs, open squares are the “C” TDEs, and the gray open circles are the “D” TDEs. The solid black line is the line of best fit and the dashed black lines represent plus/minus 1$\sigma$ from the best-fit line. The Class “D” objects were not included in the fit.

more and more similar events are found, Swift will continue to be a key tool in understanding their high-energy emission.

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**Facilities:** Swift (UVOT) (Roming et al. 2005)

**Software:** linmix (Kelly 2007)

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