Distinguishing Tidal Disruption Events from Impostors

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Abstract

Recent claimed detections of tidal disruption events (TDEs) in multi-wavelength data have
opened potential new windows into the evolution and properties of otherwise dormant su-
permassive black holes (SMBHs) in the centres of galaxies. At present, there are several
dozen TDE candidates, which share some properties and differ in others. The range in prop-
erties is broad enough to overlap other transient types, such as active galactic nuclei (AGN)
and supernovae (SNe), which can make TDE classification ambiguous. A further compli-
cation is that "TDE signatures" have not been uniformly observed to similar sensitivities
or even targeted across all candidates. This chapter both reviews those events that are un-
usual relative to other TDEs, including the possibility of TDEs in pre-existing AGN, and
summarises those characteristics thought to best distinguish TDEs from continuously ac-
creting AGN, strongly flaring AGN, SNe, and Gamma-Ray Bursts (GRBs), as well as other
potential impostors like stellar collisions, "micro-TDEs," and circumbinary accretion flows.
We conclude that multiple observables should be used to classify any one event as a TDE.
We also consider the TDE candidate population as a whole, which, for certain host galaxy
or SMBH characteristics, is distinguishable statistically from non-TDEs, suggesting that at
least some TDE candidates do in fact arise from SMBH-disrupted stars.

1 Introduction

A TDE is a star disrupted by a SMBH. The TDEs discussed in previous chapters span
a range of observed characteristics, including candidates detected first or only in X-rays,
optical, or UV light, and with or without broad H/He, coronal, or Bowen emission lines. All
are energetic transient events consistent with arising from galactic nuclei and are not known
to have re-occurred.

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Yet there are non-TDE transients—large AGN flares, SNe near or projected on the nucleus—with potentially similar features. Even some "normal," continuously accreting AGN may vary over timescales longer than some TDE candidates have so far been monitored. The range of TDE properties, which can overlap those of other transient types, suggests that there is no one observable that distinguishes TDEs unambiguously from impostors. Nor has the developing field of modelling TDE formation and emission found such a "smoking-gun."

For the time being, we must rely on the standards of jurisprudence and require a preponderance of evidence, a suite of distinguishing features. We also can employ statistical arguments to test the authenticity of at least some TDE detections. What are those features and arguments?

In this chapter, we first discuss those current TDE candidates whose properties are rare or new among claimed TDEs and examine the reasons to favour the TDE explanation. Then, for the remaining TDE candidates, we review those observables that are generally interpreted as TDE signatures, comparing them to what is known about continuously accreting AGN, AGN with strong flares arising from disk instabilities, SNe, and GRBs, as well as other potential impostors like stellar collisions, "micro-TDEs," and circumbinary accretion flows. Lastly, we explore using TDE demographics, specifically the projected offset relative to the galactic nucleus, the SMBH mass, and the stellar mass and star formation history of the host galaxy, to distinguish them statistically from non-TDE sources.

2 Unusual TDE Candidates

On-going time-domain surveys, and comprehensive follow-up campaigns, are continuously revealing new flares and transients in galactic nuclei. Some objects initially thought to be TDEs have been reclassified due to the subsequent detection of similar, non-TDE transients, e.g., F01004-2237 (Tadhunter et al. 2017), after the discoveries of OGLE17aaj (Gromadzki et al. 2019) and AT 2017bgt (Trakhtenbrot et al. 2019b, see Sect. 3.2.2), illustrating the challenge of disentangling TDE emission from other peculiar nuclear transients. Here we discuss unusual classes of objects that are still considered TDE candidates, but that are represented by only one or a handful of members. The coming era of RubinObs/LSST and *eROSITA*, when thousands of new TDE candidates will be identified, should reveal the true nature of these classes.

2.1 PS1-11af

PS1-11af is interpreted as a partial TDE (i.e., a disruption of the envelope of the star, leaving the core intact) by Chornock et al. (2014). Absorption features became apparent in the UV spectrum 24 days post flare that bear a similarity to P-Cygni troughs observed in SNe. Yet the apparent velocities of these features ($\sim 13,000$ km s^{-1}) are too high for material in homologous expansion near a SN photosphere. Furthermore, fits to the SED with a blackbody model show that the radius of the emitting ejecta does not increase and the temperature does not decrease, as would be expected for SN evolution. PS1-11af has a blue colour that evolves weakly over time, a common characteristic of optically-detected TDEs (e.g., van Velzen et al. 2011; Gezari et al. 2012). The amount of accreted mass needed to power the observed luminosity is low ($\sim 0.002\ M_\odot$), which Chornock et al. (2014) ascribe to the partial stellar tidal disruption. In this scenario, optical photons would be reprocessed from the accretion

disk to higher (X-ray) energies (e.g., Strubbe and Quataert 2009; Guillochon and Ramirez-Ruiz 2013), which requires contemporaneous X-ray coverage to confirm this hypothesis. Lacking the observations in this energy range, Chornock et al. (2014) can only propose that a partial stellar tidal disruption explains the available data, but the picture remains necessarily incomplete, underscoring the importance of simultaneous multi-wavelength coverage in unveiling the physics driving transient phenomena.

2.2 ASASSN-15lh

ASASSN-15lh was first interpreted as the most luminous SN ever detected (Dong et al. 2016). Its optical spectrum is devoid of hydrogen and helium features and contains broad absorption features between 3000–4100 Å. One such feature is attributed to OII λ4100, which is also seen in hydrogen-poor superluminous SNe (e.g., Quimby et al. 2011). However, an additional OII λ4400 feature observed in SNe is not present. This discrepancy, together with the location of ASASSN-15lh in the center of a non-starforming massive galaxy, prompted Leloudas et al. (2016) to consider ASASSN-15lh as a TDE (see also Krühler et al. 2018; van Velzen 2018; Mummery and Balbus 2020). The inferred SMBH mass from simple galactic scalings exceeds 10^8 $M_\odot$, implying that a solar-mass, solar-radius star would be swallowed whole rather than disrupted, but Leloudas et al. (2016) point out that a spinning SMBH would tidally disrupt the star and produce a transient (see also Margutti et al. 2017). As a result, ASASSN-15lh, if indeed a TDE, could then be used to infer the SMBH spin, a property that is challenging to constrain with most other methods.

Another peculiar property of ASASSN-15lh is its double-peaked UV light curve (its optical light curve is single-peaked). This bimodality, also observed in the TDE candidate AT2018fyk (Wevers et al. 2019a, see below), is unusual and difficult to explain under both the SN and TDE interpretations. Leloudas et al. (2016) propose that the first peak is powered by circularisation of the debris, while the second is from accretion; the timescales are roughly consistent with those expected from a spinning SMBH. Alternatively, Coughlin and Armitage (2018) and Vigneron et al. (2018) argue that both the double peaked light curve and the apparent high SMBH mass can be explained if the TDE is due to the secondary in a SMBH binary system. Still, the nature of this TDE candidate is disputable; Godoy-Rivera et al. (2017) argue that the evolution of ASASSN-15lh's photospheric radius, its radiated energy, and the implied event rate are all more consistent with those of H-poor superluminous SNe than TDEs.

2.3 PS16dtm

The transient PS16dtm, discovered in a Narrow Line Seyfert 1 (NLSy1) galaxy, was interpreted as a TDE rather than as a SN or arising from intrinsic AGN variability (Blanchard et al. 2017). The light curve exhibits no colour evolution during the $\sim$ 100 day plateau, similar to other optical TDEs (see van Velzen et al. 2020b, Optical Chapter). The optical spectrum has traits similar to NLSy1s, with Balmer and multi-component FeII emission lines, further arguing against a SN interpretation. Blanchard et al. (2017) rule out AGN variability, given the two orders-of-magnitude increase in optical/UV flux within $\sim$ 50 days and the decrease in X-ray flux after the optical/UV flare; they ascribe this behaviour to obscuration of the pre-existing AGN X-ray corona by the stellar debris disk formed by the disrupted star. The rise in the light curve is followed by a plateau at roughly the Eddingtion luminosity inferred for the SMBH and then a decline.

While this source is a strong TDE candidate, its spectrum, which is AGN-like, is very different than those of many optical TDEs (see van Velzen et al. 2020b, Optical Chapter). Indeed, Moriya et al. (2017) point out that PS16dtm's flare can be explained by AGN activity: increases in the accretion disk luminosity can spur radiatively driven winds that cause shock waves to propagate within the broad line region (BLR). Interactions between the shocks and BLR clouds can convert kinetic energy of the ejecta into radiation, producing transient luminosities and timescales that match those observed in PS16dtm.

2.4 AT2018fyk

AT2018fyk is a TDE candidate with a photometric UV/optical evolution remarkably similar to ASASSN–15lh, i.e., with a secondary maximum in its light curve. Margutti et al. (2017) ascribe the second peak in ASASSN–15lh's light curve to temporal evolution in the opacity of the ejecta, which allows UV radiation to escape and produce the secondary maximum. They point out that the observations are consistent with a spinning black hole disrupting a main-sequence star as a trigger for the ASASSN-15lh flare. Despite the similarities in light curve evolution, the timescales for AT2018fyk are significantly shorter than for ASASSN–15lh, and high amplitude, erratic X-ray variability is observed for AT2018fyk from the early phases.

AT2018fyk's optical-to-X-ray luminosity ratio (L_{opt}/L_X) evolves like that of ASASSN–15oi, suggesting that similar physical processes are at play. Wevers et al. (2019a) argue that both the L_{opt}/L_X evolution and the secondary maximum in the UV/optical light curve can be explained as a tidal disruption with a relativistic pericenter, as Leloudas et al. (2016) suggested led to the double-humped light curve in ASASSN–15lh. A relativistic pericenter favours disk formation on short ($\sim$ months) timescales, compared with the typical timescale of $\sim$years (van Velzen et al. 2019). Gezari et al. (2017) note that the formation of an accretion disk on similarly short timescales may explain the peculiar L_{opt}/L_X observed in ASASSN–15oi.

Another peculiarity of AT2018fyk is the apparent decoupling of the X-ray from the UV/optical emission, about 80 days after peak. This is reminiscent of the late time X-ray detection in ASASSN–15lh, while the UV/optical lightcurve steadily declines. Margutti et al. (2017) postulate that, in ASASSN–15lh, the X-ray emission may not in fact be related to the transient and may arise instead from the host galaxy nucleus, which would favour an interpretation that the flare was caused by a stellar explosion rather than a TDE. Should the X-ray emission be due to a TDE from a massive spinning black hole, the X-ray emission would fade over time. A similar observational test can be brought to bear on AT2018fyk by monitoring its X-ray emission over the time span of years.

In the optical spectra of AT2018fyk, Wevers et al. (2019a) detect low ionisation potential Fe II emission lines like those identified in ASASSN–15oi at late times. These lines are thought to form in dense, optically thick gas in an accretion disk-like structure, favouring the rapid disk formation scenario. These lines are observed frequently in high accretion rate NLSy1s, suggesting that the physical conditions in some TDEs and AGN are similar. Arguments against the AGN interpretation for this event include the absence of galactic (narrow or broad) emission lines, a pre-flare X-ray non-detection, and IR colours consistent with a quiescent galaxy.

2.5 Summary

There is not one selection mechanism that can be used to distinguish among potential explanations for transient events. Classification instead relies on the preponderance of evidence

and may still not be definitive (e.g., ASASSN-15lh). Some transient phenomena have characteristics of both SNe and TDEs (e.g., PS1-11af), AGN and TDEs (e.g., AT2018fyk), or are hosted in known active galaxies (e.g., PS16dtm), requiring care in distinguishing among flares in a pre-existing accretion disk within the high variability tail of the AGN population, the tidal disruption of a star in the vicinity of an already active black hole, or a supernova in the centre of a galaxy.

The next several sections discuss how we might differentiate TDEs from the signatures of AGN (and strongly flaring AGN), SNe, GRBs, and other potential impostors, based on photometric and spectroscopic clues as well as statistical arguments.

3 Distinguishing TDEs from AGN

Dozens of TDEs are now claimed to have been detected. The uncertainty in this number reflects the inhomogeneity of TDE definitions, incompleteness in the TDE observables, and the lack of a unifying theoretical framework. TDEs should differ from AGN in the details of their accretion, i.e., the disruption of a single star leading to the quick, inside-out formation of a small, initially inclined disk (or flow) that then disappears on a shorter timescale than typical of the more continuous nature of AGN accretion.

Yet there is much we do not know about AGN variability, particularly about the extremes of continuous variability and about instabilities in the accretion disk that may produce transient flaring. The discovery of new variable AGN classes such as hyper-variable and "changing-look" AGN, which show dramatic weakening and/or strengthening in their broad Balmer emission lines, complicates efforts to identify TDEs unambiguously. Even long-term AGN variability may be a problem; the relevant timescales for TDEs with evolved stellar progenitors (which are not the main focus here) could be far longer than for main sequence (MS) stars. Much theoretical work remains to predict TDE observational signatures and to ascertain which, if any, are unique to TDEs.

In the following discussions, we consider what may distinguish TDEs from continuously accreting AGN, including those that are highly variable, and, more problematically, from the flaring caused by AGN disk instabilities. An even bigger challenge is presented by a new class of events—combining TDE- *and* AGN-like observables—that may arise when a TDE occurs in a pre-existing AGN (e.g., Merloni et al. 2015; Chan et al. 2019; Ricci et al. 2020). In §3.2.2, we briefly discuss the few such objects detected to date, reflecting our limited knowledge at the time of this writing.

The guidelines presented below tend to err on the conservative side: we are more interested here in purity than completeness in TDE classification. As a result, TDEs that occur in galaxies with even mild signs of nuclear activity, e.g., Seyfert-like emission line ratios, otherwise strong [O III] $\lambda5007$ emission, or persistent archival X-ray emission, would be excluded by our criteria. Yet counting hybrid systems will be critical in building complete and unbiased TDE samples.

3.1 TDEs Versus Continuous AGN

The obvious difference between TDEs and steady-state AGN is that TDEs are fundamentally transient phenomena, transitioning from quiescence to near-Eddington luminosities in a few weeks, and then back to quiescence within a few years to even decades (Rees 1988; Stone et al. 2013; van Velzen et al. 2019). This opens the possibility of monitoring

several state transitions in the accretion flow, which goes from near- (or super-) Eddington to sub-Eddington and eventually becomes radiatively inefficient at low accretion rates (Jonker et al. 2020). Long term monitoring of TDEs should be pursued to reveal the details of such state transitions.

Debris disks from the tidal disruption of main sequence stars are very compact, as the star is disrupted near the SMBH with low angular momentum. If the stellar debris circularises efficiently, the size of the compact disk formed is twice the tidal disruption radius, or ~ 10–$100 R_g$ where $R_g = G M_{BH}/c^2$. In contrast, AGN disks are expected to be much more extended, as gas is supplied from farther distances (e.g., Alexander and Hickox 2012, and references therein).

Another difference between TDE and stable AGN is that TDE disks may be fed at super-Eddington rates, while (low-redshift) AGN are usually considered to be accreting at sub-Eddington levels. As a result, TDEs and these AGN would have different disk structures, i.e., the super-Eddington TDE disks would be geometrically and optically thick and produce optically thick winds (Strubbe and Quataert 2009; Lodato and Rossi 2011; Dai et al. 2018). As the accretion rate drops with fallback rate, the disk and wind densities will also decrease, lowering the electron scattering opacity. This behaviour can explain the narrowing of the TDE hydrogen and He II $\lambda 4686$ emission lines with decreasing luminosity described below, as the line width in a scattering dominated medium scales with the opacity (Roth and Kasen 2018). The higher He II/Hα ratio observed in TDEs (also discussed below) can arise from the higher accretion levels and inner disk temperatures compared to AGN, although detailed modelling on using this ratio to directly probe the disk structure is still lacking.

The absence of hard X-ray emission in the TDEs observed so far, compared with the X-ray power-law spectrum with $\Gamma \sim 1.9$ common to AGN (as discussed below), suggests fundamental differences in the disk corona. Possible explanations include: 1) the typical duration of AGN accretion is much longer than a TDE lasts, so the corona forms only for AGN; 2) the magnetic field strength and configuration is different in TDEs than in AGN, leading to less efficient coronal production.

3.1.1 Summary of Observable Distinctions

Some continuously accreting, but variable, AGN may be identified as new, blue, and/or X-ray detected nuclear transients and thus misclassified as TDE candidates. Consequently, it is essential that we consider the breadth of known AGN properties—light curves, colors, spectral shapes and lines, and variability, across optical, UV, and X-ray wavelengths—in defining criteria that may distinguish TDEs. In what follows, we discuss possible criteria and demonstrate how they may be used to assess the data for the two best-studied TDE candidates, ASASSN-14li and ASASSN-15oi. Given that strongly flaring AGN may have properties distinct from the continuous AGN population, posing a different and perhaps greater challenge to TDE classification, we discuss other appropriate strategies in §3.2.

Features that may favour a TDE over other AGN activity include:

1. steeper (month-long) and brighter (change of several magnitudes) rise in optical/UV flux;
2. relatively narrow luminosity peak, with characteristic timescale of months;
3. smooth, power-law decline in light curve, sometimes following a $t^{-5/3}$ trend;
4. ~ 0.2 mag bluer in g-r around peak emission;
5. hot, constant $T \sim 2$–4×10^4 K blackbody in optical/UV emission;
6. absent to weak [O III] $\lambda 5007$ emission, and narrow emission line ratios suggestive of star formation rather than AGN photoionisation;

7. very broad ($> 15{,}000\ \mathrm{km\,s^{-1}}$) He II $\lambda 4686$ and Balmer optical emission lines that narrow as they weaken;
8. luminous He II $\lambda 4686$ line emission, with He II/Hα flux ratio $\gtrsim 1$;
9. weak, or even absent, Mg II $\lambda 2800$ line emission;
10. softer X-ray spectrum, in terms of photon index ($\Gamma \geq 3$) and/or prominence of low-temperature emission component ($kT_{bb} = 0.04$–0.12 keV; see the Saxton et al. 2020, X-ray Chapter);
11. less rapid ($>$ hours) X-ray variability;
12. no recurrence of transient behaviour.[1]

No TDE candidate observed to date has been shown to possess all these features. Indeed, depending on the conditions, some TDEs may not generate certain features. Those TDEs with the most features above, e.g., ASASSN-14li and ASASSN-15oi, are considered the strongest TDE candidates. We discuss these two events in light of the list given above, before addressing each of the listed features in more detail.

ASASSN-14li Here is how the optical, UV, and X-ray observations of ASASSN-14li map to the criteria listed above. 1) It displayed a ΔUVW2 (*Swift*) of -4.1 and a Δg of only -0.4, where these variations in magnitudes were measured with respect to the host galaxy pre-flare archival measurements (Holoien et al. 2016b); 2) The peak of this event was not observed; 3) The UV/optical decline over the first six months of monitoring was initially fit with an exponential (Holoien et al. 2016b), but this emission was later fit with a $t^{-5/3}$ decline over a longer time interval of approximately 250 days. After this, the UV/optical light curve levelled off to a more shallow decline (Brown et al. 2017); 4) The $g - r$ colour was roughly 0.4 mag during early monitoring, but was highly affected by host contamination. The event was still quite blue, with UVM2 brighter than U (*Swift*) by a difference exceeding 0.5 mag, for at least the first 100 days of monitoring (Holoien et al. 2016a); 5) The optical/UV continuum can be fit with a blackbody with $T \approx 3.5 \times 10^4$ K, and this temperature remained almost unchanged for the first 175 days of monitoring (Hung et al. 2017).

Furthermore, 6) optical spectra indicate [O III] $\lambda 5007$/H$\beta \ll 1$ (Holoien et al. 2016b, and see also Fig. 2 in this chapter); 7) The optical emission lines initially showed broad wings with widths of $\sim 10{,}000\ \mathrm{km\,s^{-1}}$, although these widths narrowed significantly, with only a narrow component of width $\sim 1500\ \mathrm{km\,s^{-1}}$ after 100 days (Holoien et al. 2016b). The optical emission lines in the later spectra from this event are among the narrowest seen in TDEs; 8) While He II/Hα varies, this ratio was > 1 for several epochs and generally exceeded 0.5 (Hung et al. 2017); 9) No Mg II $\lambda 2800$ emission was seen in UV spectroscopy (Cenko et al. 2016).

Lastly, 10) the X-ray spectrum was soft and could be fit with a $kT = 51$ eV blackbody (Miller et al. 2015); 11) X-ray variability *was* detected in this event: a stable quasi-periodic oscillation of roughly 131 seconds was identified (Pasham et al. 2019); 12) No recurrence has been observed.

In summary, 14li meets most of the criteria for distinguishing a TDE from other AGN activity. The most prominent exceptions are for criteria 4 and 11: the earliest (closest to peak) $g - r$ measurement was only 0.2 (but this might be due to host contamination), and the event exhibited rapid X-ray variability in the form of a QPO. Additionally, since the peak was not observed, it is not possible to assess whether the characteristic rise and fall timescales are on the order of months (criterion 2). Finally, optical emission lines were somewhat narrow

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[1]One possible exception is if a TDE occurs in a binary SMBH. In this case, the TDE may be perceived as recurring transient behaviour when the X-ray light dims due to the interaction with the second SMBH.

compared to other putative TDEs (criterion 7), although these lines did narrow over time in a manner that seems characteristic of TDEs.

ASASSN-15oi Next, we consider ASASSN-15oi. 1) It displayed a ΔUVW2 (*Swift*) of -6.8 and a ΔV of only -1.2 (Holoien et al. 2016a), where once again these variations in magnitudes were measured with respect to the host galaxy pre-flare archival measurements; 2) The peak of this event was not observed; 3) A UV/optical decline similar to $t^{-5/3}$ could be fit to the first 100 days of observation, before the flux at these wavelengths dropped precipitously. While the flux initially declined steadily in all bands, the inferred bolometric flux (from a thermal fit to the optical/UV data) remained steady for approximately the first 50 days before entering a decline (Holoien et al. 2018). As with ASASSN-14li, the initial UV/optical decline could alternatively be fit with an exponential (Holoien et al. 2016a); 4) The *g-r* measurement was not published, but UVM2 was brighter than U (*Swift*) by at least 1.0 mag during the first 50 days of monitoring (10–60 days post-discovery) and by at least 0.5 mag for 40 days after that (Holoien et al. 2016a). 5) During roughly the first 15 days of monitoring, the optical/UV continuum could be fit with a blackbody of roughly $T \sim 2 \times 10^4$ K. The inferred temperature *increased* to about 4×10^4 K over the next 15 days and stayed at that temperature for at least the next 70 days (Hung et al. 2017).

In addition, 6) the [O III] lines do not appear prominently in the spectra, although there is an unidentified broad feature near 5000 Å, which can be seen at 21 days post-discovery in the host-subtracted spectrum. Likewise, Hβ does not appear prominently, although it may be blended with He II in the earliest spectrum (Holoien et al. 2016a, and see also Fig. 2 in this chapter). 7) The He II λ4686 emission line had a width (FWHM) of roughly 20,000 km s^{-1} in a spectrum taken seven days after discovery, which narrowed to approximately 10,000 km s^{-1} at 21 days (Holoien et al. 2016a). 8) While He II appears prominently in the spectrum, no clear detection of any hydrogen lines can be made (Holoien et al. 2016a); 9) No Mg II emission was seen in UV spectra (Alexander Dittmann et al., in prep.).

Finally, 10) the X-ray spectra were soft and could be fit with blackbodies with $kT \sim$ 40–50 eV; 11) No rapid X-ray variability has been reported; 12) No recurrence has been observed.

In summary, 15oi meets nearly all the aforementioned criteria to distinguish a TDE from other AGN activity, except for those specific to the peak of the light curve (criteria 2 and 4), which was not captured for this event.

3.1.2 UV to Optical Light Curve

The light curves of TDE candidates are characterised by a dramatic increase in optical and UV luminosity, with an observed variability of over three magnitudes (e.g., van Velzen et al. 2011), a narrow luminosity peak spanning a timescale of months (e.g., Gezari et al. 2009; Guillochon and Ramirez-Ruiz 2013), and a smooth power-law decline, which sometimes follows $t^{-5/3}$, the predicted mass fall-back rate (Rees 1988; Phinney 1989b).

In comparison, the light curves of variable AGN are dominated by more stochastic variability that lacks such dramatic increases in brightness. On timescales of months, the variability of the continuous AGN population rarely exceeds 0.1 mag (Fig. 1; see, e.g., Vanden Berk et al. 2004; MacLeod et al. 2010; van Velzen et al. 2011; MacLeod et al. 2012; Caplar et al. 2017, and references therein). Although this *typical* AGN optical variability amplitude increases towards longer timescales, it does not exceed Δmag ~ 1, even over decades. Indeed, only the most extreme tail of the AGN variability distribution, with few sources in wide-field surveys, reaches Δmag ~ 2 (top panels of Fig. 1; see, e.g., MacLeod et al. 2012;
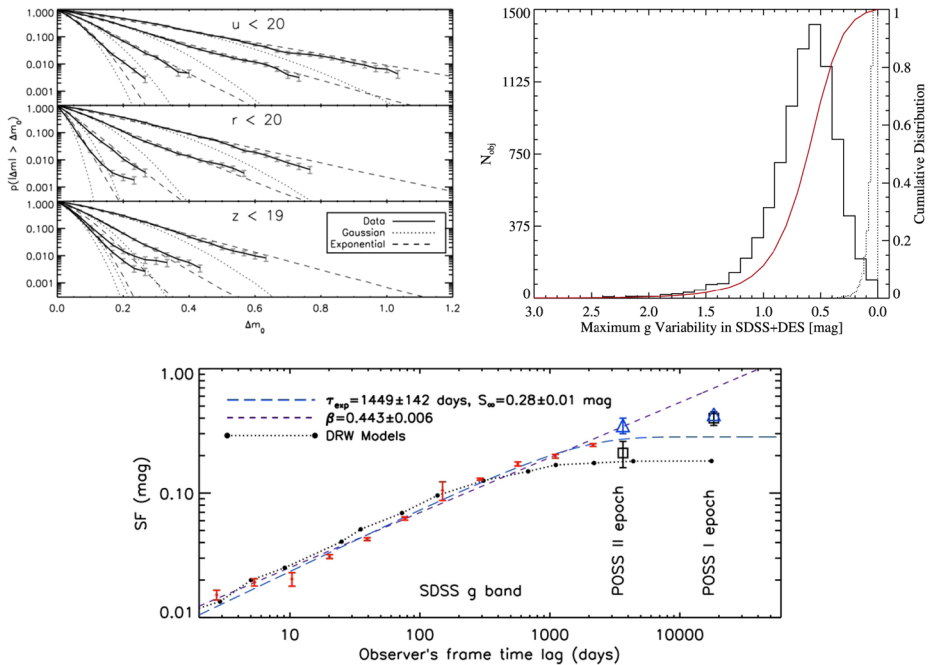
Fig. 1 Optical variability of normal, persistent (non-flaring) AGN. *Top-Left:* Distribution of UV/optical flux variations of quasars in the SDSS+POSS study of MacLeod et al. (2012). In each panel, different solid lines trace quasar variability on timescales spanning 1–30 days, 50–150 days, 200–400 days, and 1400–3000 days—the former being relevant to the rise-time of most TDEs. *Top-Right:* Distribution of optical flux variations in DES+SDSS broad-line AGN, over a period of ~ 15 years (adopted from Rumbaugh et al. 2018). The cumulative distribution function (red line) indicates that only $\sim 10\%$ of AGN show $|\Delta mag| > 1$ over this long period and are claimed to be highly variable on all timescales. *Bottom:* AGN variability on multiple timescales described through a structure function (SF), a measure of the *rms* variability of an AGN sample over any given time separation. This example (again from MacLeod et al. 2012) shows SDSS measurements over several years (red points) and combines them with POSS data for the longer-timescale measurements (large symbols). The different lines are phenomenological fits to the data. On timescales of months, AGN typically vary by < 0.1 mag, while TDEs show up as $\gtrsim 1$ mag transients (i.e., corresponding to SF $\gtrsim 1$ mag over < 100 days). Thus, normal, persistent (non-flaring) AGN essentially never show the month-long sharp optical flux increase seen in TDEs

Graham et al. 2017; Rumbaugh et al. 2018). Likewise, AGN typically do not show smooth and steady variability structure, such as the power-law decline seen in TDEs.

Some observed changing-look AGN stay at their peak optical luminosity for years (e.g., Runnoe et al. 2016). While there are TDE candidates detected in X-rays over a similar timescale (Lin et al. 2017; Jonker et al. 2020), the optical flare fades much more quickly. Furthermore, although the decays in some changing-look AGN light curves approximate a $t^{-5/3}$ decline (e.g., Merloni et al. 2015; Trakhtenbrot et al. 2019a) or permit a $t^{-5/3}$ solution (e.g., Runnoe et al. 2016), perhaps suggesting triggering by TDEs, many of these extremely variable AGN wane differently (Ruan et al. 2016) and/or lack the smooth decline expected from the fallback of debris from a TDE (Gezari et al. 2017).

The evolution of optical colours can also be used as a selection criterion for TDEs in ground-based optical surveys. Optically-discovered TDEs are characterised by a long-lasting blue continuum that resembles a blackbody of a few $\times 10^4$ K. Unlike SNe, which typically undergo significant colour evolution over a few weeks, TDEs and AGN can keep

a constant colour for a longer period of time ($\sim$years). The g-r colour of TDEs at peak emission (< -0.2 mag) is typically bluer than for AGN (> -0.1 mag; Fig. 12 in van Velzen et al. 2011). The observed bluer-when-brighter trend for AGN is consistent with the simple scenario of a geometrically-thin, optically-thick (i.e., Shakura-Sunyaev like) disk with variable accretion rates (e.g., Pereyra et al. 2006; Hung et al. 2016). If the observed AGN flare is an intrinsic property of the accretion disk, the classic thin disk model would predict a g-r of ~ -0.1 mag. Although intrinsic extinction in AGN is hard to estimate, it will only make the g-r colour in AGN flares redder than the predicted value, separating them further from TDEs in the optical colour space.

3.1.3 Optical Spectrum

A few key features in the optical spectra of TDE candidates can be used to differentiate them from persistent AGN. Vanden Berk et al. (2001) and the references therein provide more information about the typical UV/optical spectral energy distribution (SED) and emission lines in AGN. For complementary composite spectra in the NIR and UV, see Glikman et al. (2006) and Shull et al. (2012), respectively.

Hot, Constant Blackbody Continuum The continuum colour variability also differs between AGN and TDEs. Quasars are known to be bluer when brighter (e.g., MacLeod et al. 2010; Ruan et al. 2014). Although there is substantial scatter in this relationship, it provides additional leverage in identifying TDEs where no colour evolution is observed due to the constant blackbody temperature that produces the optical/UV continuum emission.

Weak [O III] Line The AGN narrow line region (NLR) is primarily ionised by the accreting black hole, and can span scales of order ~ 0.1–1 kpc, with some dependence on the AGN continuum luminosity (e.g., Bennert et al. 2002, 2006; Mor et al. 2009; Hainline et al. 2013, 2014). The [O III] $\lambda 5007$ emission line is one of the most prominent in the NLR and has been used both to map out the size of the NLR (e.g., Schmitt et al. 2003b,a) and as a proxy of the intrinsic (bolometric) AGN luminosity (Kauffmann et al. 2003; Heckman et al. 2005; LaMassa et al. 2010; Pennell et al. 2017). Due to the much larger size scale of the [O III] $\lambda 5007$ emitting region (and thus of the NLR) compared with the BLR, this line responds slower to the change in the ionising continuum than the broad emission lines (i.e., $\gg 100$ years; see, e.g., Peterson et al. 2013).

TDEs tend to have weak to no [O III] $\lambda 5007$ emission, with [O III]/Hβ and [N II]/Hα emission line ratios consistent with photoionisation from star formation or LINER-like activity on the BPT (Baldwin et al. 1981; Kewley et al. 2006) diagram. Even TDE hosts with Seyfert-like line ratios, e.g., ASASSN-14ae (French et al. 2017), ASASSN-14li (French et al. 2017), and iPTF16fnl (Onori et al. 2019), generally have weak line strengths that would classify them as LINER-like on a WHAN (Cid Fernandes et al. 2010) diagram. We explore the range of AGN signatures in TDE host galaxies in the French et al. 2020, Host Galaxies Chapter.

On the other hand, galaxies with significant nuclear photometric and spectroscopic variability and strong [O III] emission are more likely to be hosting highly variable AGN, especially if the emission line ratios are within the Seyfert region of the BPT diagram. The emission line ratios of many changing-look AGN are generally consistent with those of AGN (e.g., Runnoe et al. 2016; Ruan et al. 2016). Thus, our guideline 6 in §3.1.1 would exclude most strong AGN and most changing-look AGN. We note that, while some luminous quasars have relatively weak [O III] emission (e.g., Netzer et al. 2004), their UV/optical continuum luminosities tend to be far higher than those of TDEs and could be used as a discriminant.

Fig. 2 Continuum-subtracted optical spectra of UV/optical-bright TDEs, most of which show He II line emission of comparable luminosity and FWHM to Hα
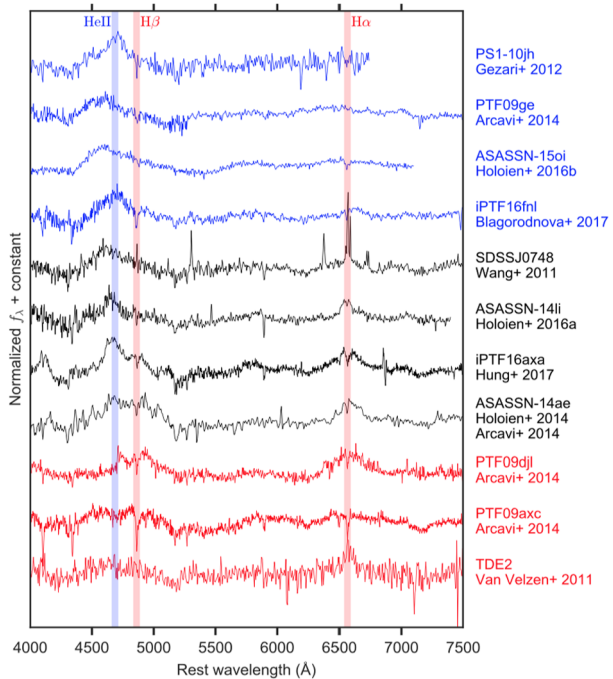
What do we miss with this conservative cut, where we have prioritised TDE sample purity over completeness by selecting against strong [O III] emission? We would neglect, for example, the TDE candidate PS16dtm (Blanchard et al. 2017), whose host is a NLSy1. Also excluded would be transients in the 2017-bgt class (Trakhtenbrot et al. 2019b; see below), whose nature is unclear. The presence of some activity in a galaxy does not eliminate *a priori* the possibility of a TDE, although caution should be used in such cases.

Broad, Narrowing Balmer and He II Lines The emission line velocity widths and their time-dependent changes provide another way of distinguishing between AGN and TDEs. Near peak, the typical Hα and He II λ4686 FWHM of TDEs are both of order 10^4 km s^{-1} and often exceed 15,000 km s^{-1} (Fig. 2). Only a fraction of a percent of the Hα and Hβ lines in SDSS AGN (which may have problematic spectral decompositions) are as broad as in TDEs, i.e., $\gtrsim 15,000$ (Fig. 3). This distinction may arise from the structure and dynamics of the BLR around SMBHs with certain masses (Laor 2003). Thus, line width is a reasonably good discriminator, but, depending on the overlap in the distributions for TDEs and AGN, may not be iron-clad.

Whenever AGN spectra do have noticeable He II λ4686 emission, the line profiles and widths are generally comparable to those of Hβ (and thus also Hα). While accurate measurements for individual AGN are often challenging, given the weakness of the He II feature and the fact that it is blended with several [Fe II] emission features, the resemblance between He II and Hβ can be seen in stacked spectra (e.g., Fig. 3 of Boroson 2002).

The temporal evolution of the velocity line widths in response to changes in the photoionising continuum provides an even better way of distinguishing between TDEs and AGN. In changing-look quasars, which are likely to contaminate TDE searches, the broad emission lines broaden as they weaken (LaMassa et al. 2015; Runnoe et al. 2016). This is the basis for
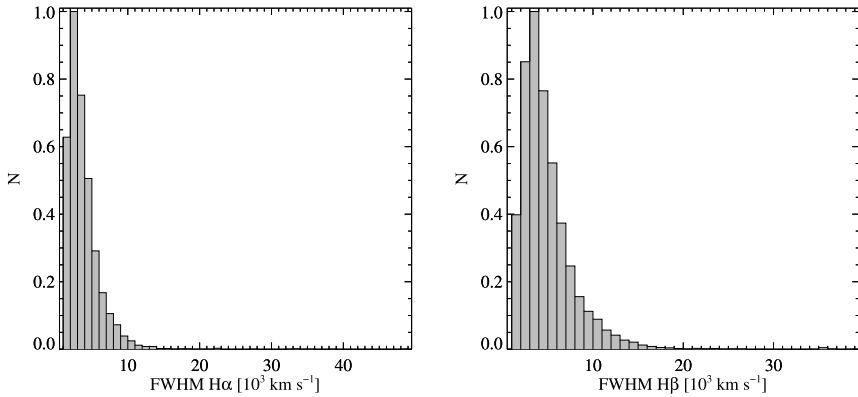
Fig. 3 The FWHM distributions for the Hα and Hβ broad emission lines in SDSS DR7 quasars, taken from the spectral decompositions of Shen et al. (2011). Only a small fraction of sources have Balmer lines that are broader than ∼ 15,000 km s⁻¹. Given that such extremely broad Balmer lines are often seen in TDEs, Balmer line width can serve as a discriminant between TDE candidates and persistent AGN

Fig. 4 The variation in the He II/Hα flux ratio over time for a collection of TDEs. Observing this flux ratio ≳ 1 in at least one spectral epoch distinguishes optical/UV TDE candidates from most AGN. However, the ratio evolves with time, and so a single spectral epoch may miss the He II line if it appears at a different time. Figure reproduced from Hung et al. (2017)
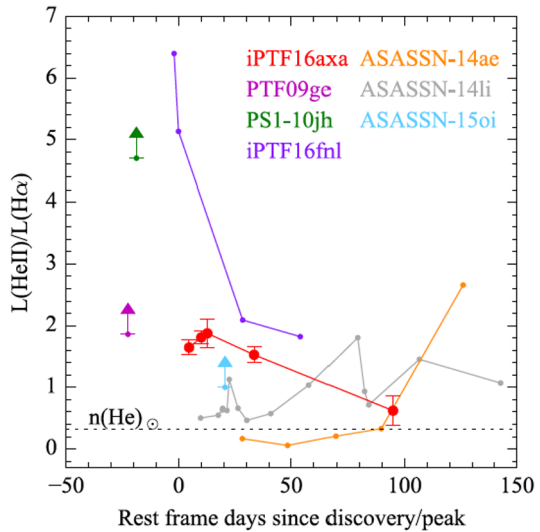
reverberation mapping in AGN (e.g., Peterson 1993) and the opposite of what is observed for TDEs (Holoien et al. 2016b).

High He II/Hα Ratio The spectra of many UV/optical-bright TDEs have prominent He II λ4686 line emission. The line luminosity is typically of order 10^{41} erg s⁻¹ at its brightest, much stronger than Hβ and comparable to (or even stronger than) Hα (Fig. 2). Therefore, a He II/Hα flux ratio ≳ 1 in at least one spectral epoch is a hallmark of UV/optical-bright TDE candidates, as is He II/Hβ ∼ 1.

There are potential exceptions. One possible case is TDE2 (van Velzen et al. 2011, the bottom spectrum in Fig. 2), but its spectrum is low signal-to-noise. Another is PS1-11af (Chornock et al. 2014), although that event showed no emission lines at all in its spectrum.

Because the He II/Hα flux ratio is observed to evolve with time, we note that a single spectral epoch may miss the He II line if it appears at a different time (Fig. 4).

In comparison, while AGN spectra do exhibit broad He II λ4686 emission, it is typically weak compared to the Balmer lines. The He II/Hα flux ratio in the SDSS quasar composite is ∼ 0.005 (Vanden Berk et al. 2001). From the theoretical side, photoionisation modelling of the BLR in AGN also gives He II/Hα < 1, although the goal of such work is usually to reproduce normal AGN spectra and not extreme outliers.

Like other high-ionisation species and transitions, He II comes from closer to the central engine than the Balmer lines (e.g., Grier et al. 2013) and is extremely responsive to continuum changes in the AGN (as in Korista and Goad 2004), whereas Hα is the least responsive of the Balmer lines. Thus, with a large (UV) flare in the AGN continuum (even if the SED shape does not change), it may be possible to boost the He II/Hα ratio temporarily. That said, while Peterson and Ferland (1986) describe a (moderate) flare in the AGN reverberation-mapping poster child, NGC 5548, that substantially boosts the He II emission, it is always weaker than Hβ. As a caveat to the above, we must mention that the measurement of the flux of the He II λ4686 line can be affected by blending with the N III λ4640 line, which can be excited by Bowen fluorescence (e.g. Leloudas et al. 2019; Onori et al. 2019; Nicholl et al. 2020). Medium resolution spectroscopy may be helpful in deblending these two components.

3.1.4 UV Spectrum

The UV spectra collected of TDEs so far (Fig. 5) have revealed striking differences with respect to AGN, although the sample is currently small. As of this writing, there are only two TDE in quiescent galaxies with published UV spectra: iPTF15af (Blagorodnova et al. 2019) and AT2018zr (Hung et al. 2019), also known as PS18kh (Holoien et al. 2019). There is at least one more event with an unpublished UV spectrum, ASASSN-15oi (Alexander Dittmann et al., in prep.). Additionally, there is a near UV spectrum of PS16dtm (Blanchard et al. 2017), but, because that event took place in a NLSy1, we exclude it for the present purpose of distinguishing TDE from AGN. ASASSN-14li (Cenko et al. 2016) and iPTF16fnl (Brown et al. 2018) also have published UV spectra, but are not in quiescent host galaxies.

These systems generally lack certain low-ionisation emission lines that are common in most AGN, in particular Mg II λλ2796, 2804. The exception is AT2018zr, which displayed a broad emission feature consistent with Mg II in five spectra taken between roughly 20 to 60 days after r-band peak. However, the equivalent width of Mg II dropped steadily in time, and, by the final spectrum, the line had all but disappeared, while an absorption feature appeared at a blueshifted velocity consistent with the velocity ($15,500 \, \mathrm{km \, s^{-1}}$) inferred from the Balmer lines in the optical spectrum (Hung et al. 2019). This rapid spectral variability distinguishes the event from most AGN in its own right.

Equally interesting is the general absence of C III] λ 1909 emission in the TDEs, a line seen in most AGN UV spectra. Adding to the differences is the general strength of N III] λ 1750 emission, a line which shows up prominently in only approximately 1% of SDSS AGN. Here again AT2018zr is an exception, but only in the sense that its N III does not show up clearly in emission, although it may be contributing to absorption at that wavelength. While the rare, so-called "N-rich QSOs" do have this emission line, they generally also have a strong C III] line accompanying it, as well as Mg II, which is not the case for TDEs (Jiang et al. 2008; Cenko et al. 2016).

There are broad absorption features in some UV TDE spectra, although these too distinguish themselves from broad absorption line quasars (BALQSO). TDEs with clear or
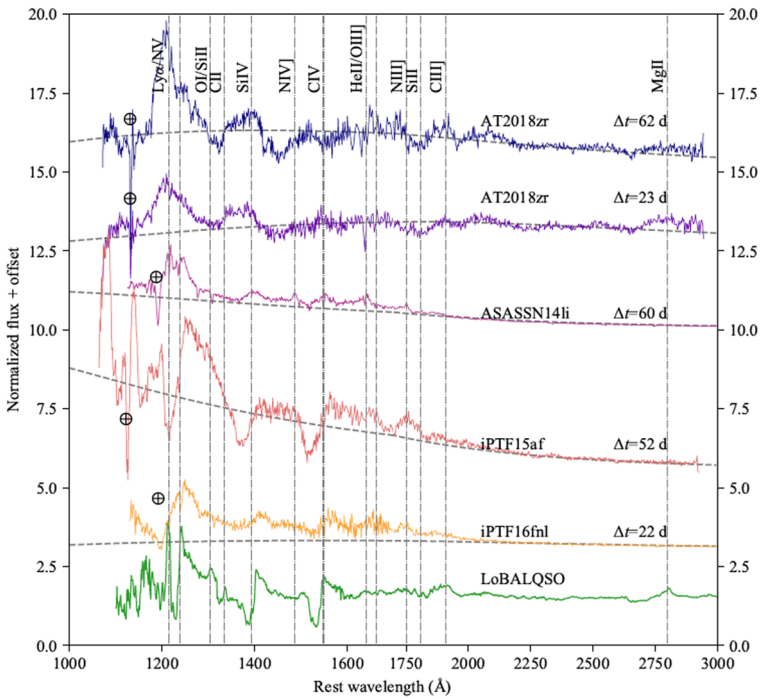
Fig. 5 Ultraviolet spectra from four TDEs, including two epochs for AT2018zr, compared to a low-ionisation broad absorption line QSO (LoBALQSO) composite spectrum. At least three of the TDE spectra lack Mg II λλ2796, 2804 emission. This figure appears in Hung et al. (2019) and is reproduced here with the permission of the American Astronomical Society

tentative absorption include iPTF16fnl, iPTF15af, and AT2018zr (PS18kh). In these cases, the absorption seems to correspond to the C IV λλ1548, 1551, Si IV λλ1394, 1403, and N V λλ1239, 1243 lines.

The FWHM of these lines is roughly in the range 5000–10,000 $\mathrm{km\,s^{-1}}$, quite similar to BALQSOs. However, in iPTF16fnl and iPTF15af, the centroid of the absorption lines is near enough to the line centre so that the absorption represents velocities from nearly 0 to 10,000 $\mathrm{km\,s^{-1}}$, blending smoothly into the emission on the red side. In contrast, the centroid of the absorption lines in BALQSOs is often blueshifted by at least 10,000 $\mathrm{km\,s^{-1}}$, and so the absorption is completely detached from the emission, with a broader wing on the higher velocity side (Blagorodnova et al. 2019). AT 2018zr (PS 18kh) once again displays its own unique behaviour, with possible broad absorption centroid velocities of 15,000 $\mathrm{km\,s^{-1}}$; these absorption lines were also highly variable, becoming increasingly prominent with time in the five spectra taken over approximately 40 days.

Of the TDEs with published UV spectra in quiescent hosts, both exhibit broad absorption lines at some point in time. This fraction is higher than that of BALQSOs. Blueshifted BALs in QSOs are thought to arise from fast-moving outflows. If the QSO/BALQSO dichotomy is largely due to viewing angle effects, then outflows in TDEs may subtend a larger solid angle than in AGN (Hung et al. 2019).
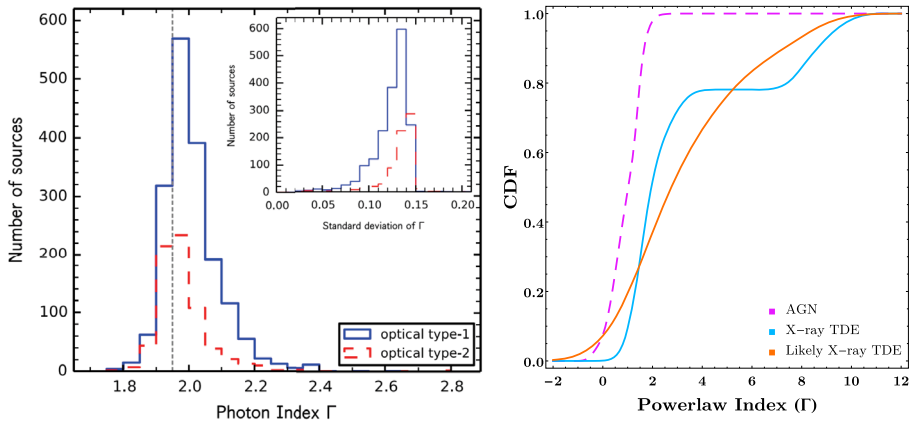
Fig. 6 Comparison of power-law photon index Γ for the X-ray spectra of AGN and TDEs. *Left:* Distribution of photon indices of ~ 2500 AGN observed with *XMM-Newton*. The AGN have non-thermal spectra with power law photon indices ranging from 1.7–2.4. Figure adapted from Liu et al. ([2016](#)). *Right:* Cumulative Γ distributions for events classified as X-ray TDEs (cyan curves) or likely X-ray TDEs (orange) by Auchettl et al. ([2017](#)) compared with AGN detected in the *Chandra* Deep Field South (magenta; Tozzi et al. [2006](#); Xue et al. [2011](#)). Both TDE distributions from Auchettl et al. ([2017](#)) include jetted TDE candidates, which tend to have harder X-ray spectra than thermal TDEs and photon indices more like AGN. Observing a nuclear transient with a steeper (softer) X-ray SED ($\Gamma \gtrsim 3$) may strongly favour a TDE interpretation

3.1.5 X-Ray Spectrum

AGN activity could potentially mimic the X-ray emission arising from TDEs. In this section, we compare observations of X-ray emission from AGN and TDE candidates, focusing on those that might help us distinguish between the two types of sources. The Saxton et al. 2020, X-ray Chapter has more information on the X-ray properties of TDEs.

Thanks to its high-sensitivity and good sky coverage, the *ROSAT X-ray Observatory* (Truemper [1982](#)) discovered the first TDE candidates. These nuclear transients had a peak X-ray luminosity of $L_x \sim 10^{44}$ erg s^{-1}, were associated with galaxies that showed no evidence of (prior) AGN emission, produced light curves that decayed following a $t^{-5/3}$ power-law, and had X-ray spectra that were best described with a $\sim 10^{5-6}$ K blackbody or with a very steep power-law index ($\Gamma = 3$–7, Fig. 6; Grupe et al. [1995](#); Brandt et al. [1995](#); Bade et al. [1996](#); Komossa and Bade [1999](#); Grupe et al. [1999](#); Greiner et al. [2000](#)). Since *ROSAT*, the capabilities of the *Neil Gehrels Swift* Gamma-ray Burst Mission, the *Chandra X-ray Observatory*, and *XMM-Newton Space Observatory*, including increased effective area, spectral coverage, spatial resolution, and/or spectral resolution, have dramatically changed our ability to characterise the detailed spectral evolution of TDE candidates, leading to discoveries including rapid variability and, in Swift J1644+57, possible jet formation (Bloom et al. [2011](#); Burrows et al. [2011](#)).

AGN and TDEs are quite different in the nature and appearance of their broad-band X-ray spectra. In AGN, around 10% of the bolometric luminosity is released as non-thermal X-ray continuum up to ~ 100 keV, as magnetic processes in and/or above the disk form a relativistic electron cloud that is partly cooled due to the inverse Comptonization of the thermal disk photons. In the 2–10 keV band, this continuum is typically modelled as a simple power-law, whose index is determined by the temperature distribution of the electrons and by the number of electrons that each UV seed photon encounters. In AGN, the average

Fig. 7 Cumulative distribution function of line-of-sight hydrogen column density (N_H) for TDEs classified as a X-ray TDEs (cyan curves) or likely X-ray TDEs (orange) by Auchettl et al. ([2017]). These TDEs are significantly less absorbed compared to AGN found at similar redshifts in the *Chandra Deep Field South* (magenta; Tozzi et al. [2006]; Xue et al. [2011]). It is not yet clear whether this difference is real or due to observational bias
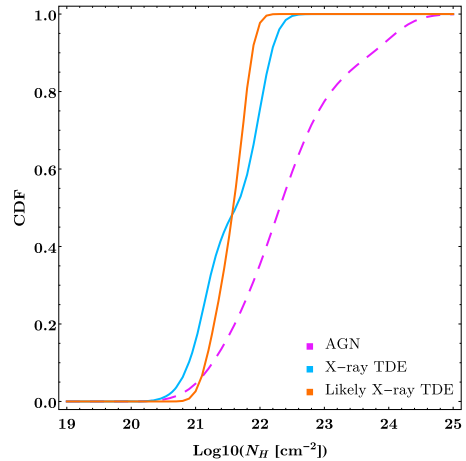
2–10 keV spectral index is 1.9, with a spread from ~ 1.7 to 2.4 at the most extreme (Fig. 6; Liu et al. [2016]).

In contrast, most thermal TDEs show X-ray emission that is dominated by a multicolor blackbody component with a temperature of 50–100 eV, e.g., ASASSN-14li (Miller et al. [2015]; Holoien et al. [2016b]; Brown et al. [2017]). In some cases, there is an additional weak hard X-ray tail, e.g., ASASSN-14li (Kara et al. [2018]) and XMMSL1 J074008.2-853927 (Saxton et al. [2017]). For ASASSN-14li, Kara et al. ([2018]) suggest that the hard excess beyond the blackbody arises from additional inverse Compton scattering of disk photons by relativistic electrons in an X-ray corona. This additional Comptonization component appears to contribute more to the spectrum as the source evolves over time, either due to the accretion rate dropping or due to the delayed formation of an X-ray corona. Most recently, Wen et al. ([2020]) show that a "slim disk" accretion model adapted to SMBHs can successfully describe the multi-epoch X-ray spectra of ASASSN-14li.

Another observed distinction is that TDEs are significantly less absorbed compared to AGN found at similar redshifts (Fig. 7). We note, however, that this difference may arise from observational bias. A column density of 10^{22} cm^{-2} would completely absorb the emission of soft TDEs with a 50 eV thermal spectrum and hinder their detection.

The thermal-dominated X-ray spectra of TDEs such as ASASSN-14li differ from those of a wide range of AGN, from Type 1 (unabsorbed) to Type 1.9 (absorbed), all of which have non-thermal emission (Fig. 8). Two NLSy1s, 1H0707-495 and Ark 564, have been proposed as Eddington-limited or even super-Eddington AGN. Even these extreme accretion AGN show non-thermal X-ray emission and are distinct from ASASSN-14li.

While thermal TDEs have softer X-ray spectra than AGN (Lin et al. [2011]; Auchettl et al. [2017]), the seemingly separate class of jetted TDEs, such as Swift J1644+57, is characterised by strong X-ray emission up to ~ 100 keV and an AGN-like photon index (Bloom et al. [2011]; Burrows et al. [2011], see also Sect. 5). Complicating the picture further are observations showing that some thermal TDEs spectrally harden as they evolve (e.g., ASASSN-14li; Kara et al. [2018]), while others show little variation. For the time being, we conclude only that a nuclear transient with a steeper (softer) X-ray SED ($\Gamma \gtrsim 3$) is more likely to be a TDE than an AGN.

Fig. 8 Comparison between the X-ray spectra of the well-known thermal TDE ASASSN-14li (black) and AGN of different types, including MCG-6-30-15 (red), NGC 1365 (green), 1H0707-495 (blue), and Ark 454 (cyan). Even Eddington-limited NLSy1 AGN (in blue and cyan) do not show as steep an X-ray spectrum as thermal TDEs. Figure from E. Kara
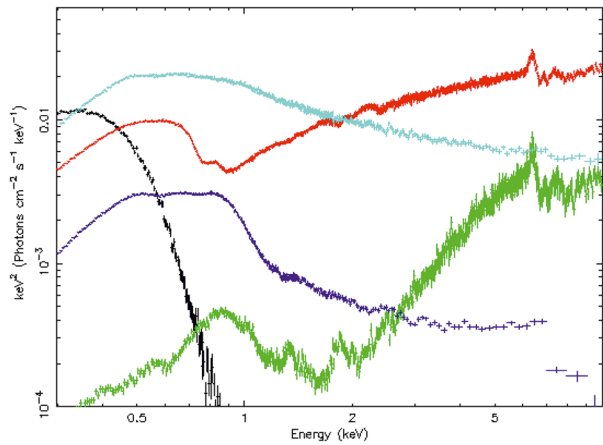
3.1.6 X-Ray Variability

The variable X-ray emission observed in persistent AGN spans timescales from seconds to months and years, with an amplitude often much larger than at optical wavelengths (for the same source; e.g., Lanzuisi et al. 2014, and references therein). In contrast, the X-ray (and optical/UV) light curves of TDEs show a steady, months-long structure. Hence, measuring a transient's X-ray light curve with a short cadence and over years, and comparing it to the UV/optical light curve, may prove an important tool in identifying TDEs by excluding those AGN that vary on much shorter or longer timescales.

It is not yet clear how strongly the observed decay rate of the X-ray light curve discriminates between TDE and variable AGN. The self-regulating nature of the SMBH accretion in AGN can produce an X-ray light curve that declines as $t^{-(1.5-2.0)}$ (e.g., Hopkins and Hernquist 2009). While a power-law of $t^{-5/3}$ has been associated with some TDE optical/UV light curves and the first X-ray light curves, the observed temporal evolution of soft X-ray emission from current X-ray and likely X-ray TDE candidates (Auchettl et al. 2017) follows a wide variety of power-laws, consistent with fall-back, accretion, and disk emission (e.g., Evans and Kochanek 1989; Phinney 1989a; Cannizzo et al. 1990; Cannizzo and Gehrels 2009; Cannizzo et al. 2011; Lodato and Rossi 2011; Guillochon and Ramirez-Ruiz 2013), with the majority shallower than $t^{-5/3}$. Guillochon and Ramirez-Ruiz (2013) suggest that such shallow declines arise when TDEs are viscously delayed (i.e., the time it takes for material to accrete is slow).

Many AGN of extreme X-ray variability have been discovered thanks to the photon-counting nature of X-ray facilities, as well as the long integration times used for some sources and for certain extragalactic fields. These AGN remain poorly understood, due to the frequent lack of simultaneous data at other wavelengths. The X-ray spectra of "X-ray changing-look" AGN (Matt et al. 2003; Bianchi et al. 2012; Ricci et al. 2016) have been well modeled by occulting clouds transiting into and out of the line-of-sight towards the AGN, alternately masking and uncovering the central engine. However, the X-ray spectra of some optical changing-look AGN, with their weakening or strengthening of broad Balmer lines, cannot be ascribed to variable extinction. When observed in the dim state, the X-ray spectra do not show features of obscuration that extinguishes and reprocesses the X-ray emission, but rather are consistent with a model where the intrinsic X-ray emission diminished significantly (e.g., LaMassa et al. 2015, 2017; Husemann et al. 2016). The processes responsible

for driving the X-ray variability are unknown, but there may be a link between the Eddington ratio and spectral state of the AGN due to mechanisms that operate at the scales of the inner accretion disk, similar to the spectral state transitions observed in stellar mass black hole binaries (e.g., Noda and Done 2018; Ruan et al. 2019).

TDEs tend to show relatively little variation in column density with time (Auchettl et al. 2017); after an initial drop, N_H remains roughly constant over at least several hundred days in both ASASSN-14li and -15oi (Wen et al. 2020). Thus, observing an evolving column density is a possible way of distinguishing some AGN from TDEs. We note, however, that the X-ray TDEs discovered to date tend to have lower N_H than AGN (Fig. 7), which may limit the measured N_H variation. For cases where declining absorption can be excluded as the cause of X-ray brightening, the distinction between TDE and X-ray variable AGN is less apparent. For instance, in the Seyfert 1.9 galaxy IC 3599, TDEs were alternately invoked (Campana et al. 2015) and ruled out (Grupe et al. 2015) to explain the observed, recurring X-ray flares.

3.2 Differentiating TDEs from Flaring AGN

3.2.1 Accretion due to Disk Instabilities

In contrast with steady-state AGN disk accretion, accretion events arising from AGN disk instabilities might be relatively quick and deplete only the innermost AGN disk, a scale comparable to that expected for TDEs. Indeed, fast and coherent instabilities in the innermost parts of the disk seem to be required to explain significant variability events in accreting SMBHs, as this is where most of the (continuum) radiation is produced (see, e.g., Lyubarskii 1997; King et al. 2004, and the discussion in Cannizzaro et al. 2020). Such events might even produce higher accretion rates and luminosities than during the steady-state and/or quiescent stages. In other words, AGN flares might share many similarities with TDEs.

Thermal, viscous, gravitational, and radiation-pressure instabilities have all been suggested to occur in AGN disks (e.g., Janiuk et al. 2002; Jiang et al. 2013 and references therein). Below is a brief review of the main aspects of such instabilities and their implications. We generally follow the discussion in Saxton et al. (2015).

Accretion disks may attain a limit-cycle behaviour, which can be generally divided into three phases: in the 1) *quiescent phase*, material initially accumulates at a slow rate and fills the inner region of the disk. The disk structure and properties then slowly evolve until the disk becomes unstable, leading to the 2) *rise and outburst phase*, where the instability typically leads to a runaway heating, increasing the local viscosity, scale height of the disk, and the local accretion rate (Cannizzo 1996). This process eventually changes the accretion rate and produces a rapid depletion of the unstable region, whose material then accretes onto the SMBH. Such a fast accretion episode leads to a flaring of the SMBH. As the inner disk depletes, when the matter is accreted into the black hole faster than it is replenished, the accretion flare goes through the 3) *decay phase*, leading to a new quiescent phase and the next accumulation cycle.

The disk-instability model thus predicts *repeated* flares. The possibility of observing multiple flares depends on the typical duty-cycle timescale. For an unstable disk model to explain the known TDE candidates, the timescale for the limit-cycle must be sufficiently long, given the non-detection of repeated TDEs to date.[2]

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[2]The (in)ability to detect such repeated flares naturally also depends on their amplitudes, which are not necessarily as high as the flare that led to the identification of the TDE candidate.

The overall depletion of the inner unstable disk is likely to occur on the timescale τ_{dep} for material to viscously accrete from the truncation radius, the outermost part of the unstable region down to innermost stable circular orbit (ISCO). The initial rise should be fast, as the accretion begins from the innermost region, and then slower, up to the timescales for the material in the outermost truncation radius region to accrete down to the SMBH. Given the mass enclosed in this region and the accretion rate, one can estimate a typical timescale for the overall rise and fall:

$$\tau_{\text{dep}} = M_{\text{inner}}/\dot{M}. \tag{1}$$

The enclosed mass of the inner disk is given by

$$M_{\text{inner}} = \int_{R_0}^{R_{\text{trunc}}} \rho(r)\, 2\pi r\, H(r)\, dr, \tag{2}$$

where R_0 is the radius of the ISCO, R_{trunc} is the truncation radius, $\rho(r)$ is the disk density, and $H(r)$ is its height. For a Shakura-Sunyaev thin disk (Shakura and Sunyaev 1973) and typical values, expressed in gravitational radii, the enclosed mass is

$$M_{\text{inner}} = 6 \times 10^{-4} \alpha^{-8/10} M_6^{11/5} \dot{M}_{\text{Edd}}^{-3/10} \left[\left(\frac{R_{\text{trunc}}}{R_{\text{g}}} \right)^{5/4} - \left(\frac{R_0}{R_{\text{g}}} \right)^{5/4} \right] M_\odot, \tag{3}$$

where α is the viscosity parameter, and the accretion rate is given in units of the Eddington-limited accretion rate, $\dot{M}_{\text{Edd}} \simeq 1.4 \times 10^{24} M_6\ \text{g s}^{-1}$, for a SMBH mass M_6 in units of $10^6\ M_\odot$ (Saxton et al. 2015). The depletion time τ_{dep} (with typical truncation radius of a few tens of gravitational radii) is then

$$\tau_{\text{dep}} \sim 0.33\, \alpha_{uns}^{-8/10} M_6^{6/5} \dot{M}_{\text{Edd}}^{-3/10} \left[\left(\frac{R_{\text{trunc}}}{R_{\text{g}}} \right)^{5/4} - \left(\frac{R_0}{R_{\text{g}}} \right)^{5/4} \right] \text{months}. \tag{4}$$

In other words, τ_{dep} is equivalent to the viscous timescale of a thin disk at the truncation radius, and α_{uns} is the viscosity in the unstable region, rather than the typical viscosity operating during the regular accretion phases.

There are many uncertainties both in understanding the disk instability process and in the estimates of the typical timescales and accretion rates, making this approach simplified at best. Much depends on the choice of R_{trunc} and on whether these instabilities occur there. Nevertheless, the reasoning here suggests that the timescales for the rise and fall of such flares for low mass SMBHs (up to $\sim 10^7\ M_\odot$) are on the order of weeks to months, while the timescales for more massive SMBHs are probably too long for the flares to be classified as fast transients. In other words, disk-instability flarings potentially masquerade as TDEs of MS stars only for lower mass SMBHs. In addition, for SMBH masses larger than $\sim 10^8\ M_\odot$, the ionisation region is also Toomre unstable ($Q < 1$, self-gravity).

Interestingly, the timescales of both TDEs and disk-instability flares depend on the SMBH mass, but through different scalings. This difference could potentially be used to distinguish between the models. Nevertheless, better comprehension of both the TDE process (including TDE debris disk circularisation) and disk instabilities that lead to flares is needed before reliable predictions and comparisons can be made.

As noted by Saxton et al. (2015), the overall timescale for the duty-cycle, and hence for repeating flares, is determined by the filling or viscous time at the truncation radius.
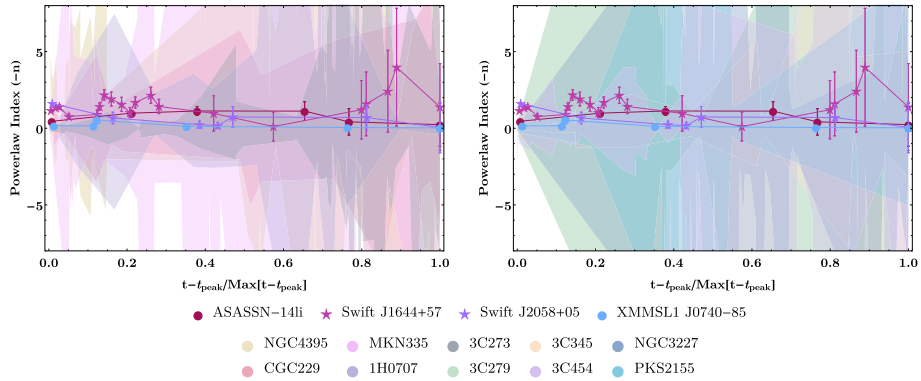
Fig. 9 Comparing the smoothness of X-ray light curve decay for TDEs and AGN flares. Auchettl et al. (2018) determine the best fit power-law index ($-n$) for TDE and AGN samples as the time of peak goes to infinity, assuming $L \propto (t - t_{peak})^{-n}$. Here we plot n as a function of $t - t_{peak}$, where t_{peak} is the time in which the peak luminosity is detected. The sources decay over different timescales, so $t - t_{peak}$ is normalised by its maximum value for each source. The derived power-law indices for AGN vary significantly over short time scales, ranging between $n \sim -10$ and $+15$. Different colour shaded bands represent the full range of these indices and their uncertainties. In contrast, the decay of a TDE flare is best fit with a power-law index between $n = 0$ and ~ -2; for most of the decay, the power-law index changes little, especially for the two non-jetted TDEs ASASSN-14li and XMMSL1 J0740-85. Figure adapted from Auchettl et al. (2018)

The viscosity in the stable region beyond the truncation radius differs from that in the inner region during the depletion, and so refilling takes far longer than the depletion and flaring timescale, i.e., decades or more for $M_{BH} \sim 10^6 \, M_\odot$. Repeated flares on such a timescale have been observed in the Sy 1.9 galaxy IC 3599, 20 years apart (Grupe et al. 2015).

Due to the uncertainties in the duty cycles of AGN, it is not always feasible to rule out recurring flare emission due to an AGN when seeking to confirm a TDE. Another difficulty is that, during an AGN flare or TDE, the change in source luminosity, relative to the pre-event upper-limits, is similar (Auchettl et al. 2018). However, Auchettl et al. (2018) find that TDE X-ray light curves decay much more coherently, even monotonically, while the rate of AGN decay varies widely with time (Fig. 9). Less than 4% of the coherent decay behaviour seen in their TDE sample could arise from sources like those in their AGN sample, suggesting that observing smooth decay can help to distinguish TDEs from AGN flares.

Galaxies hosting *known* AGN are typically excluded from TDE candidate selection, given the confusion arising from the expected AGN variability and flaring. However, galaxies hosting undetected, sub-luminous ("starved") AGN may present as quiescent. Given the low accretion rates in starved AGN (Saxton et al. 2018), their disk properties and variability could differ from those of persistent AGN, and their occasional flares might masquerade as TDEs. Gas-poor hosts are less likely to enable gas inflows to the nucleus, so flarings in starved AGN may favour "gas-intermediate" hosts, whose histories include higher rates of star formation in the past.

Saxton et al. (2018) suggest that the apparent preference of TDE candidates for "post-starburst" galaxies (see the French et al. 2020, Host Galaxies Chapter) naturally arises from the reasons above and that many of these events are in fact AGN flares. One prediction of the disk instability scenario is therefore that deeper observations of TDE candidate hosts will reveal weak AGN, either now or in the recent past, at higher rates than in other, comparably massive galaxies. However, at least for known low luminosity AGN (if defined by LINER
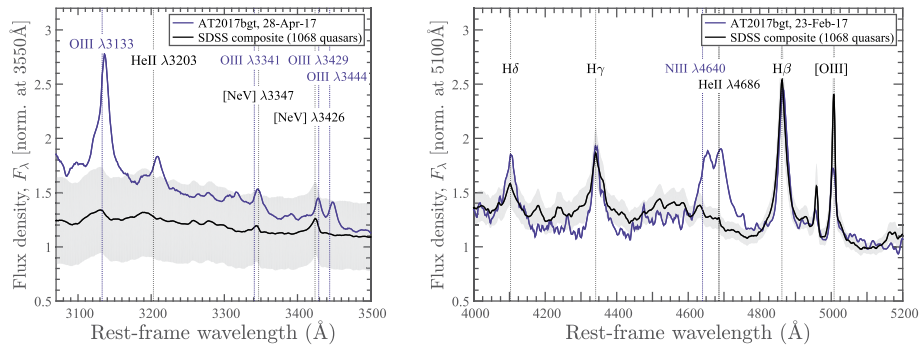
Fig. 10 Optical spectra of AT 2017bgt and unobscured AGN (adapted from Trakhtenbrot et al. 2019b). Two spectra of AT 2017bgt (blue), taken at different epochs within about two months of discovery, are compared to a composite of more than a thousand SDSS broad-line AGN (quasars) with similar hydrogen emission line widths. The broad Balmer lines and narrow forbidden [O III] λλ4959, 5007 lines of AT 2017bgt (and other events in this new class) are similar to those in the AGN. On the other hand, the prominent double-peaked emission feature near 4680 Å (*right panel*), the prominent O III λ3133 and He II λ3203 lines, and the weaker O III λλ3341, 3429, 3444 lines (*left*), are not seen in the AGN. These features arise from Bowen fluorescence, indicating an atypically strong source of high-energy (X-ray/EUV) radiation that produces intense He II emission, which in turn drives the O III and N III emission lines through multiple scatterings and excitations in an optically thick medium

emission), it is unlikely that UV/optical-bright TDE candidates arise from tail end of normal Type 2 AGN variability (Sect. 7.3).

3.2.2 Flaring of Known AGN

Trakhtenbrot et al. (2019b) identify a new class of flares from accreting SMBHs, which may be of particular importance to TDE classification. The light curves, which are exemplified by AT 2017bgt, the brightest and best-studied flare, exhibit a significant increase in UV/optical emission, followed by a long, slow decline, on timescales of a year (or more). The optical spectra show both narrow and broad emission lines, most of which resemble those of AGN, particularly NLSy1. Most importantly, AT 2017bgt-like events have a prominent double-peaked emission feature near 4680 Å, which is composed of the He II λ4686 and N III λ4640 emission lines, and several other strong O III transitions, all with widths similar to the broad Balmer lines. These lines, driven by Bowen fluorescence (BF), are not seen in normal AGN (Fig. 10), despite specific predictions (Netzer et al. 1985). Their existence in these UV-bright transients indicates that the BF process in dense gas near accreting SMBHs requires an exceptionally strong incident UV continuum.

While this new class of UV-bright flares from SMBHs was identified from only three events, including the transient in the ultra-luminous infrared galaxy F01004-2237 (Tadhunter et al. 2017) and the OGLE17aaj event (Gromadzki et al. 2019), on-going transient surveys should detect additional events of this kind. Such events are "TDE impostors," at least initially, as their early optical spectra would show a strong, broad feature near 4680 Å, which could be interpreted as He II λ4686, a common emission line in optical TDE candidates. Indeed, one of these events was originally classified as a TDE (Tadhunter et al. 2017). However, this feature, which is composed of two separate emission lines, is both narrower and weaker than the He II λ4686 emission observed in TDE candidates to date, i.e., with smaller FWHM *and* flux ratios relative to Balmer lines (see Fig. 11).

Fig. 11 Broad emission features near He II λ4686 in AT 2017bgt, and similar objects, compared to other nuclear transients (adapted from Trakhtenbrot et al. 2019b). The spectra of AT 2017bgt (blue) and the events in F01004-2237 (Tadhunter et al. 2017) and OGLE17aaj (Gromadzki et al. 2019, both in red) represent a new class of nuclear transients. Also shown are the spectra of four TDEs (from Gezari et al. 2012; Arcavi et al. 2014; Holoien et al. 2014, 2016b, in black) and of the luminous, slowly-evolving transient PS1-10adi (Kankare et al. 2017, in grey). All spectra are continuum-subtracted. The feature near 4860 Å in the AT 2017bgt-like events, which originates from He II λ4686 and the Bowen fluorescence N III λ4640 transitions, is significantly narrower than what is typically seen in most TDEs
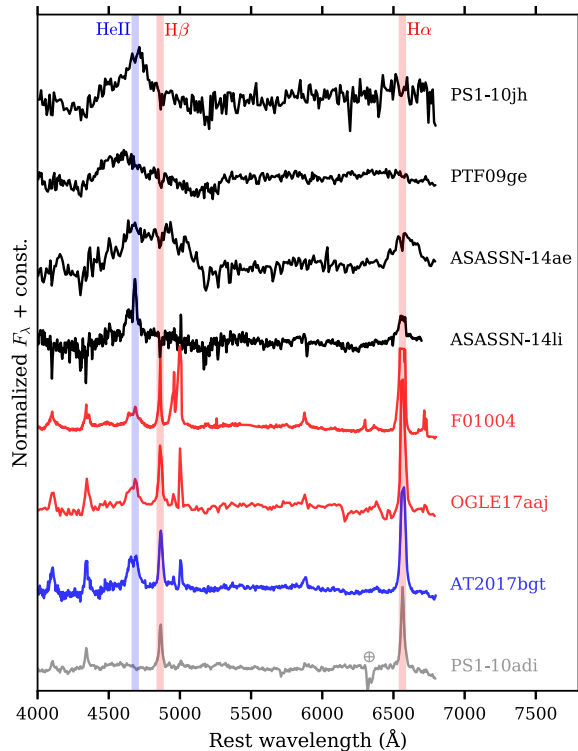
Other recently discovered transients, some of which are strong TDE candidates, exhibit BF features in their optical spectra. TDE examples include iPTF15af (Blagorodnova et al. 2019), iPTF16fnl (Onori et al. 2019), ASASSN-18pg/AT2018dyb (Leloudas et al. 2019), and ASASSN-14li, which has some evidence for such features (Holoien et al. 2016b). Newer work shows that, in a flux-limited sample, TDEs with Bowen lines (or "TDE-Bs") are as common as TDEs with only broad hydrogen lines; in a volume-limited sample, TDE-B's are the *most* prevalent of the three TDE classes considered by van Velzen et al. (2020a).

Thus, the BF mechanism appears to frequent a range of nuclear, UV/optical-bright transients, all of which are related to enhanced accretion onto a SMBH. In some cases, the optical light-curve, the peak luminosity, and the historical lack of SMBH activity, strongly favour the TDE interpretation. In other cases, where there is robust evidence for a pre-existing AGN (e.g., AT 2017bgt), we must be more prudent. While the nature of AT 2017bgt-like events remains ambiguous, the slow evolution of their light curves also argues against a "simple" TDE origin. One intriguing possibility is that these events arise from a tidal disruption stream colliding and interacting with a pre-existing AGN accretion disk. As noted by Chan et al. (2019), testing this scenario requires simulations that fully explore the geometry and orientation of the tidal stream relative to the disk, the density and velocity structure of the stream, and the properties of the unperturbed disk, as well as that predict the radiative output of the disk-stream interaction.

The flare in the well-known AGN 1ES 1927+654 (Trakhtenbrot et al. 2019a) exhibited an optical light-curve reminiscent of a TDE in rise time, peak luminosity, and decline rate. However, there were no telltale TDE features in the optical/UV spectroscopy, which instead revealed a changing-look AGN event occurring on a timescale of months. A follow-up study

(Ricci et al. 2020) speculated that the disappearance and reappearance of the X-ray emitting corona (also on timescales of months) was indeed linked to the tidal disruption of a star onto the pre-existing AGN accretion disk. This interpretation was based on qualitative agreement with models (Chan et al. 2019), which were limited in their predictive power (see more recent progress in Chan et al. 2020).

Another complex nuclear transient that occurred in a known AGN is CSS100217: 102913+404220, where the SDSS spectrum prior to the flare shows signatures of a NLSy1 galaxy (Drake et al. 2011). Drake et al. (2011) rule out a TDE based on several factors: the light curve evolution does not follow a $t^{-5/3}$ decay, the peak brightness ($M_{V,CSS} = -23$) is much higher than usually observed in TDEs ($M_V \sim -20$; see van Velzen et al. 2020b, Optical Chapter), and the fitted temperature is too low ($T = 1.5 \times 10^4$ K) compared with theoretical expectation ($T \simeq 10^5$ K). The light curve and the evolution of the narrow Balmer lines in the optical spectrum are consistent with a Type IIn supernova.

As in the case of AT 2017bgt-like events, the nature of this transient is hard to interpret. While CSS100217 could be a nuclear Type IIn SN or AGN flare, its fitted temperature is consistent with values seen in optical/UV TDEs (see van Velzen et al. 2020b, Optical Chapter), where the emission may be formed in outer shocks or reprocessing material rather than in a directly visible accretion disk. Drake et al. (2011) point out that other NLSy1 galaxies do not show the same level of optical variability and that the increase in the narrow Hα line strength after the flare died away occurred on a timescales too short to originate in the narrow line region. A focus on following up nuclear transients in AGN hosts, particularly in NLSy1 galaxies, and on quantifying the rates and range of TDEs and nuclear SNe in a control sample of quiescent galaxies, will reveal the connection between AGN and TDEs, whether it be physical or just due to mis-classification of AGN flares and/or nuclear SNe as TDEs.

3.3 Summary

Unambiguous TDE classification remains challenging, as any single observed property may be consistent with that of a persistent or flaring AGN. However, a constellation of unusual features like those cited in the previous sections and their consistency with rough expectations from theory argue that at least some TDE candidates, even unusual ones like ASASSN-15lh (Leloudas et al. 2016) and PS1-11af (Chornock et al. 2014), may in fact be tidally disrupted stars.

The observed overlap of TDE and AGN properties, particularly in the case of highly-variable AGN and AGN disk instability induced flares, complicates TDE classification and highlights the importance of archival data in constraining the level of SMBH activity prior to and long after a transient's detection. Known AGN should not be excluded from transient searches. It would be helpful to make use of existing datasets and related AGN selection criteria including: *WISE* for MIR-based AGN selection (e.g., following the criteria in Stern et al. 2012) and variability; *ROSAT* (and even *Swift*/BAT) for X-ray luminosity and X-ray SED shape; FIRST/NVSS for radio-based discrimination between galaxy star formation and AGN activity (e.g., following the SFR prescriptions of Hopkins et al. 2003); SDSS, 2dF/6dF, and earlier spectroscopic surveys, as well as relatively new efforts like GAMA and OzDES. All can be used to determine whether the transient in question is an unusual AGN or perhaps a TDE.

AGN and TDE may also be linked physically. New discoveries of dramatic, UV/optical-bright flares from accreting SMBHs, which share some TDE characteristics, raise the possibility that tidal disruption phenomena may occur in existing AGN and lead to extreme AGN

variability. From a theoretical point of view, it is not yet clear how often to expect a tidal disruption event in a pre-existing AGN. Nor do we understand why some TDEs and flaring AGN both have Bowen fluorescence lines. Observationally, we do not know at present whether TDEs in pre-existing AGN are more common than those associated with dormant SMBHs or how to cleanly distinguish TDEs from the flares of known AGN.

4 Distinguishing TDEs from SNe

At first sight, optical/UV TDEs (e.g., PS1-10jh; see van Velzen et al. 2020b, Optical Chapter) can have observed properties similar to those of core collapse (CC) SNe: light curves with peak luminosities between those of "normal" and superluminous (SL) SNe (e.g., Arcavi et al. 2014), light curve timescales like those of SLSNe (e.g., Gal-Yam 2012), and broad emission line features. Indeed, ASASSN-15lh remains a debated TDE versus SN case (see Sect. 2). However, for most TDEs, a closer look at their properties reveals stark differences with SNe.

4.1 Summary of Observational Distinctions

The events in the PS1-10jh-like class of optical/UV TDEs (see van Velzen et al. 2020b, Optical Chapter) have the following properties that are not typically seen in SNe:

1. Blue, constant colour for hundreds of days;
2. Very late-time (years) UV detections;
3. Broad emission line profiles with no blueshifted absorption;
4. Strong, broad He II;
5. No late-time narrowing of emission lines in nebular phase;
6. Accompanying X-ray flare (in some cases).

4.2 Temperature Evolution

The colour of optical TDEs, implying an effective temperature of a few $\times 10^4$ K, remains constant for weeks or even months (see van Velzen et al. 2020b, Optical Chapter and references therein). While such temperatures are observed in SNe at early times, they cool within days to much lower temperatures (see Fig. 12).

In addition, some TDEs show continued UV emission years after discovery (van Velzen et al. 2019); such long-lasting UV emission is not seen in SNe.

4.3 Spectral Line Profiles

Most SNe spectra display lines with P-Cygni profiles, which originate in expanding ejecta. The line profiles of optical/UV TDEs are generally very different, showing no absorption and sometimes asymmetric emission profiles (see van Velzen et al. 2020b, Optical Chapter and Fig. 13). Even Type IIL SNe, which show weaker P-Cygni absorption (e.g., Gutiérrez et al. 2014) compared to Type IIP SNe, are still not as emission-dominated as TDEs.

Fig. 12 Effective temperature evolution for optical/UV TDEs (circles, in days from discovery; Hung et al. 2017; Holoien et al. 2014, 2016a,b) and for hydrogen-rich core collapse SNe (squares, in days from explosion; Menzies et al. 1987; Richmond et al. 1994; Valenti et al. 2014). TDEs remain hot, while SNe cool within a few weeks. H-stripped SNe, which are not shown, cool even faster
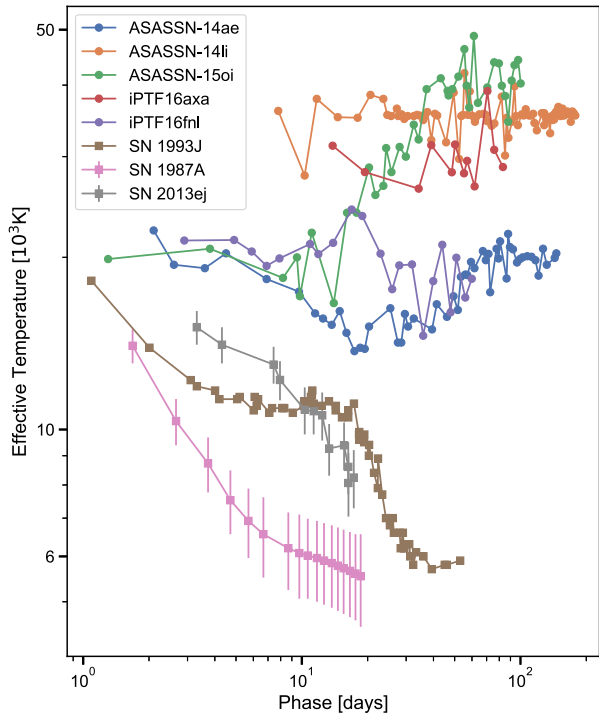
4.4 Spectral Line Species

The spectral line species in optical TDEs differ from those of any known SN. Specifically, broad He II is not seen in any SN type at a strength comparable to H, in contrast to the broad He II and Balmer lines of some optical TDEs (Fig. 13). Ca features that are ubiquitous in SNe are not seen in TDEs at all, while only a few TDEs have shown Fe features, another element that is commonly observed in SN spectra.

4.5 Spectral Line Width Evolution

The spectral lines of optical TDEs remain relatively broad even at late times (months to years after peak); in contrast, SN spectra become "nebular" on those time scales, revealing only narrow emission lines from inner slow moving material as the ejecta expand and become transparent.

4.6 X-Ray Emission

Some optical TDEs are accompanied by X-ray emission, as expected from newly formed accretion disks. Most SNe, on the other hand, do not emit in X-rays, except for cases of obvious interaction between the SN ejecta and dense circumstellar material (CSM). Furthermore, in those cases, narrow emission lines from the unshocked CSM dominate the spectra, in stark contrast to the broad lines seen in the main class of optical TDEs.

Fig. 13 Continuum subtracted spectra of optical/UV TDEs (black; Gezari et al. 2012; Arcavi et al. 2014; Holoien et al. 2014, 2016b) and of different subtypes of hydrogen-rich core collapse SNe (blue; from bottom: IIn, IIb and IIP; Kiewe et al. 2012; Barbon et al. 1995; Leonard et al. 2002). Both the spectral species and line profiles are different between TDEs and SNe
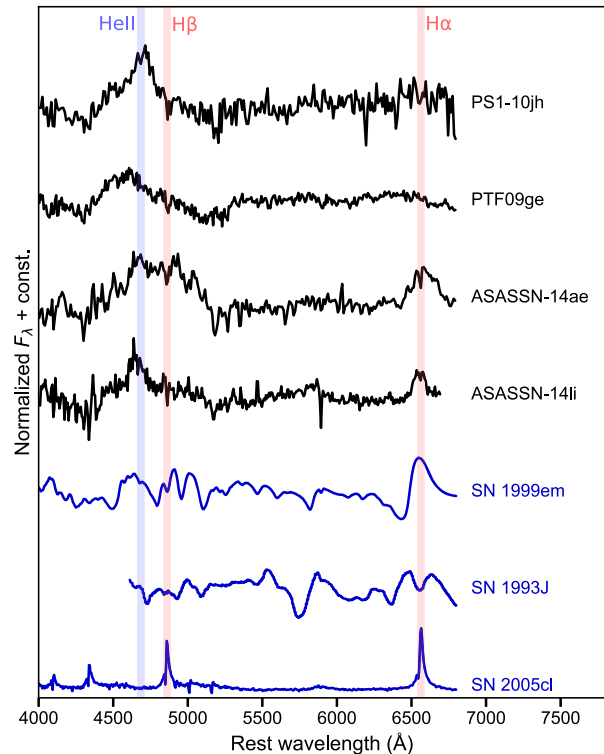
4.7 Summary

Several observational properties, which are readily measured for transients, help distinguish TDEs from SNe. This, in addition to the ample knowledge of SN populations and their typical emission properties, is the reason that there is relatively little confusion between these types of events. The notable exception is the case of ASASSN-15lh, which is a clear outlier to both known TDE and SN populations. Analysing the location of events with respect to the host galaxy centre may provide clarity; if future 15lh-like events are all found in the host centres, the TDE interpretation will be strengthened, else these sources are likely SNe.

5 Distinguishing Jetted TDEs from GRBs

The discovery of γ-ray bursts (GRBs) of cosmic origin were reported by Klebesadel et al. (1973). GRBs were a bi-modal distribution and could be divided into two categories based on the duration of their prompt emission: short and long (e.g., Kouveliotou et al. 1993). Short GRBs (SGRBs) have prompt emission (T_{90}) lasting approximately 2 sec or less, while long GRBs (LGRBs) have prompt emission from about 2 up to several thousand seconds. A more recently discovered class of "ultra-long" GRBs (GRB 111209A, GRB 121027A, and GRB 101225A) have prompt emissions at high energies from a few hundred to a few thousand seconds (e.g., Levan et al. 2014).

Jetted TDEs became a new category of TDEs after the unusual discovery of GRB 110328A by *Swift*'s γ-ray telescope (hereafter, Sw J1644+57; Burrows et al. 2011;
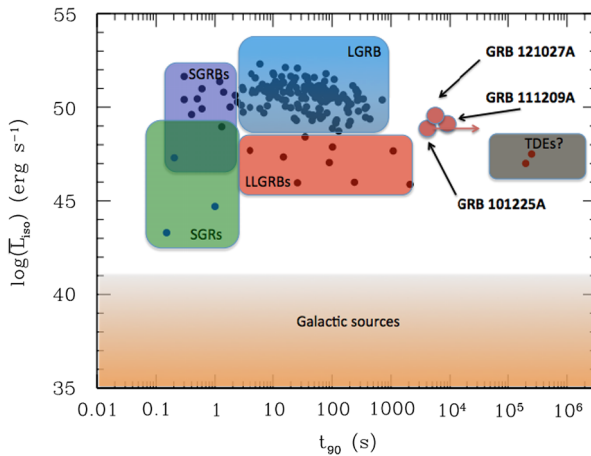
Fig. 14 Duration of burst versus approximate average luminosity over that duration for transients in the γ-ray sky. The figure compares the properties of soft-gamma repeaters (SGRs) in our own Galaxy, long- and short-duration GRBs (LGRBs and SGRBs), low-luminosity GRBs (LLGRBs), three GRB outliers (GRB 101225A, GRB 111209A, and GRB 121027A), and two very long transients thought to be jetted TDEs. Compared to GRBs, jetted TDE candidates exhibit high amplitude flaring at early times and prompt emission in X-rays lasting for weeks, i.e., t_{90} of 10^5–10^6 s. Figure reproduced from Levan et al. (2014)

Zauderer et al. 2011; Bloom et al. 2011; Levan et al. 2016). The same year, *Swift* discovered another event, Sw J2058+05 (Cenko et al. 2012), with very similar properties. In this section, we briefly describe the discovery of jetted TDEs and the primary ways in which they can be differentiated from GRBs via 1) prompt emission energy levels, 2) timescales and light curve; and 3) host galaxy association and the location of the transient within.

5.1 Prompt Emission, Timescales, and Light Curve

Jetted TDEs differ from GRBs in several ways, including high amplitude flaring at early times and prompt emission in X-rays lasting for weeks, i.e., t_{90} of 10^5–10^6 s (Fig. 14). The X-ray luminosity is also much greater (see, for example, Fig. 4 of Cenko et al. 2012). Additionally, for jetted TDEs, the X-ray light curve (after initial flaring) falls off as roughly $t^{-5/3}$. Sw J1644+57 and Sw J2058+05 have similar properties, including a X-ray light curve that slowly declined as $t^{-5/3}$ and then abruptly cut off, suggesting that the relativistic outflow shut off; see Fig. 4 of Zauderer et al. (2013) and Fig. 1 of Pasham et al. (2015).

5.2 Relationship to Host Galaxy

Another approach to distinguish jetted TDEs from GRBs is to evaluate the environment, and, if detectable, the type of host galaxy and where the transient lies within it. Long GRBs were determined to come from the deaths of massive stars based on their association with star forming galaxies, with the star-forming regions in those host galaxies, and, more specifically, with SNe themselves (see Hjorth and Bloom 2012, and references therein). Studies of the host environment (see Fong et al. 2015, and references therein) also contributed to the model of short GRBs as originating from compact object mergers, for which the discovery of GW170817 (Abbott et al. 2017) has now provided the strongest evidence. On the other hand, the jetted TDE candidates observed to-date have radio emission consistent with

arising from the centres of inactive galaxies. For example, VLBA observations localised the radio afterglow of Sw 1644+57 to the host galaxy centre (Zauderer et al. 2011); multi-wavelength observations were important to 1) localise the afterglow, as the error circle for the *Swift*/XRT was more than an arcsecond; 2) obtain redshift information (e.g., from optical spectroscopy); and 3) classify the host galaxy (especially given that there were no previous observations).

5.3 Summary

For current and future wide-field surveys (e.g., VLA Sky Survey; VLASS), Metzger et al. (2015) discuss how various types of transients may be distinguishable based on emission timescales and energies. A combination of prompt emission timescales, light curves, event energetics, host galaxy properties, and transient location relative to the host centre will help to distinguish future TDEs from GRBs. In a case where the transient is detected after the high-energy emission has faded, the work may be more difficult. However, host galaxy properties will still be useful for population-wide, statistical studies.

6 Other Potential TDE Impostors

6.1 Stellar Collisions in Galactic Nuclei

Galactic nuclei hosting SMBHs are some of the most dense and collisional environments in galaxies, with stellar densities of 10^6–10^7 pc^{-3} (see Neumayer et al. 2020, for a review). Stellar collisions and mergers could thus be abundant there (see Dale et al. 2009, and references therein), making explosive transient events far more likely. Because the densest nuclear star clusters are associated with galaxies hosting relatively low mass ($< 10^8$ $M_\odot$) SMBHs, stellar collisions may generate transient events in nuclei of similar masses to those expected to produce TDEs, leading to misidentifications. Moreover, mergers of binary stars can be induced by secular evolution in triple systems (Perets and Fabrycky 2009); in galactic nuclei, every binary forms a triple with the SMBH and is therefore potentially sensitive to such secular evolution. In other words, binary mergers could be triggered near SMBHs (Antonini et al. 2010; Antonini and Perets 2012; Prodan et al. 2015; Stephan et al. 2019), potentially mimicking TDEs.

Nevertheless, there are likely differences between TDEs and nuclear stellar collisions and mergers that could distinguish their populations individually and/or statistically. For example, mergers/collisions may produce reddened transients, perhaps similar to the merger in the V1309 Scorpii system (Tylenda et al. 2011). More generally, stellar collisions/mergers should be abundant in other dense stellar environments, such as globular clusters, so their expected spatial distribution and properties would need to be reconciled with the nuclear (by definition) environments of TDE candidates.

Another possibility is that stellar collisions and mergers near a SMBH could remove material from stars that is then accreted by the SMBH. For example, the rate of grazing collisions can be enhanced through the capture of stars inspiraling to the SMBH due to gravitational wave emission (Metzger and Stone 2017). Such grazing collisions can strip material from the stars, which would later be accreted by the SMBH or accumulate to form a disk around the SMBH and eventually produce a flare.

Other types of induced mergers and collisions near SMBHs could produce gas clouds that later accrete onto the SMBH and generate flares (e.g., SMBH-induced binary mergers,

Antonini and Perets 2012; Prodan et al. 2015). Such events might impersonate TDEs or disk instability flaring. It is not clear, however, why such induced stellar mergers should be preferentially observed in the hosts most favoured by TDEs, i.e., quiescent, Balmer-strong (QBS) galaxies and the subset of post-starburst (PSB, or "E+A") galaxies (Arcavi et al. 2014; French et al. 2016; Graur et al. 2018; see the French et al. 2020, Host Galaxies Chapter).

6.2 Micro-TDEs

The tidal disruption of stars by stellar-mass black holes potentially gives rise to a different class of transients. Such "micro-TDEs," especially when occurring in or near galactic nuclei, could be incorrectly interpreted as TDEs associated with the central SMBH. Perets et al. (2016) suggested that micro-TDEs arising from the disruption of MS stars or planets may appear as ultra-long GRBs ($\sim 10^3$ to a few $\times 10^4$ s). The timescales could be longer for evolved star progenitors, whose disruption might produce longer-term transient X-ray sources. Such micro-TDEs could masquerade as jetted TDEs detected in X-rays and γ-rays.

While micro-TDEs should occur across different environments, including dense non-nuclear stellar clusters and even in the field (Perets et al. 2016), they could also be frequent in galactic nuclei, given the highly collisional environment there (as discussed in the previous section).

Lin et al. (2018) reported a transient event in a star cluster offset by 12.5 kpc from the centre of its host galaxy ($z = 0.055$). Observational signatures of this event are similar to those of TDE candidates: the light curve decays by roughly $t^{-5/3}$ over 10 years, the X-ray spectrum is soft and well described by a thermal accretion disk that cools with decreasing luminosity, and the peak luminosity of the flare is 10^{43} erg s^{-1}. This event may be a micro-TDE of a post-MS star. The high disk temperature and long decay time suggest another possibility, that the TDE arose from a star shredded by an *intermediate*-mass black hole in the star cluster (see Lin et al. 2018, Wen et al. 2021), which would represent a new probe of that elusive black hole population.

6.3 Circumbinary Accretion Flows

Many studies (see De Rosa et al. 2019, for a review) explore the possibility of binary massive black holes accreting from a circumbinary disk (e.g., Ivanov et al. 1999; MacFadyen and Milosavljević 2008; Cuadra et al. 2009; Shi et al. 2012; D'Orazio et al. 2013; Tanaka 2013; Muñoz et al. 2020; Ragusa et al. 2020, and references therein). Tanaka (2013) suggests that a SMBH binary (SMBHB) can clear a central cavity in its accretion disk, which then appears dimmer and softer than an equivalent single AGN disk. Gas streams of 0.1 solar masses, which are intermittent on timescales depending on the binary period, then infall towards the SMBHB from the cavity's lip. The streams shock, giving rise to a TDE-like flare. If the recurrence period is long compared to the era of transient monitoring, a single detection might be misidentified as a TDE.

The recurrence period, debris velocities, and energy yields in a cavity flare depend on the SMBHB properties and need not correspond to the predicted tidal radii of stellar disruptions. Thus, the timescales for such flares might not be directly related to SMBH mass (cf. van Velzen et al. 2019). Subtler details might distinguish binary cavity flares: the steepness of their fading or their occurrence around a SMBH that is too massive for a TDE. For example, Leloudas et al. (2016) and Krühler et al. (2018) infer $M_{\rm BH} > 10^8 \, M_\odot$ for the weak-lined TDE candidate ASASSN-15lh. If SMBH binaries are a common product of the galaxy-galaxy mergers that produce post-starburst galaxies, then the cavity flare mechanism, like
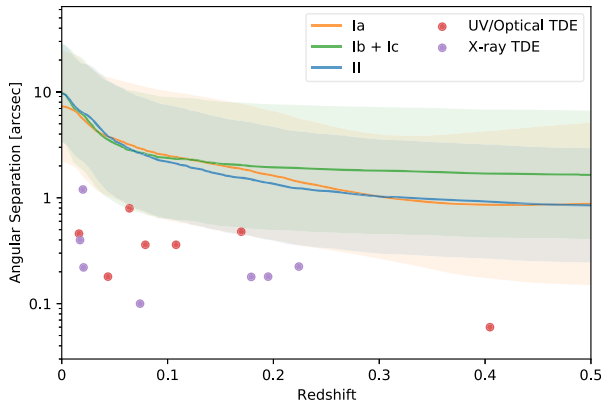
Fig. 15 Angular separation from host galaxy centre versus redshift for UV/optical and X-ray TDE samples (red and purple points, respectively) and for SNe (coloured mean lines and $\pm 1\sigma$ bands). The data are drawn from the transient-host pair catalogue of Qin et al. (in prep.). For TDEs, the angular separation uncertainties are generally unrecorded in the literature and probably dominated by the uncertainty in the position of the host's centre, especially at lower redshifts. At all redshifts, the SNe tend to lie further from the centre than TDEs, with angular offsets of over 1 dex (1.8σ) larger. This difference may arise in part from a selection effect, as certain types of SNe are likely to occur near the dense centre, but are harder to detect there, and transients may be classified as TDEs after consideration of their proximity to the nucleus

stellar tidal disruption, may favour such host galaxies; the expected rate is currently difficult to assess.

7 Distinguishing TDE Candidates Statistically

The demographics of TDE-candidates, e.g., their frequency, spatial offset from the host galaxy nucleus, and host properties, may provide evidence for their existence by *statistically* distinguishing them from impostors. The expected rates of TDEs are reviewed in the Stone et al. 2020, Rates Chapter, and TDE host galaxy properties in the French et al. 2020, Host Galaxies Chapter. Here we discuss statistical arguments suggesting that at least a fraction of TDE candidates are real, while some individual TDE detections remain ambiguous. Specifically, we compare the TDE nuclear offsets and the SMBH masses, stellar masses, and star formation histories of TDE hosts to those of AGN and SNe.

7.1 Nuclear Offsets

SNe in general have higher observed rates than TDEs (see Stone et al. 2020, Rates Chapter), and most observed SNe are significantly offset from the galactic centre (Fig. 15). However, these offsets are in part a selection effect; intrinsically, some types of SNe are more likely than others to occur near the centre. While TDEs are nuclear sources by definition (except for presumably rare cases around a recoiling BH), SNe generally follow the mass distribution of their progenitor stellar population in the host galaxy. Because TDE candidates significantly differ from typical SNe, it is hard to explain all TDE candidates as SNe, as those SNe masquerading as TDEs would need both to occur in or very near the nucleus and be unusual. Although the environments of galactic nuclei are unique, it is challenging to envision them giving rise to SNe that are rare elsewhere.
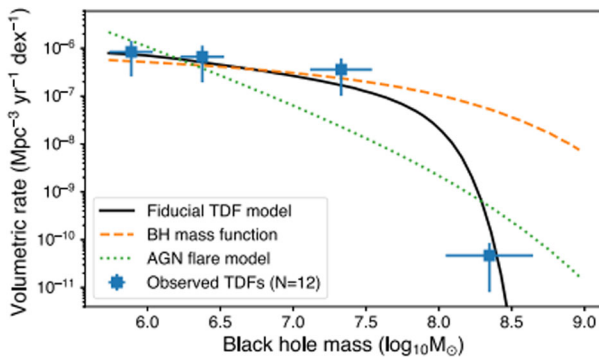
Fig. 16 Differences in expected black hole mass function for TDEs vs. AGN from van Velzen (2018). The green dotted line represents the expected volumetric rate of AGN flares, assuming that the flare reoccurrence time scales linearly with M_{BH}. This model fails to reproduce the observed volumetric rate of observed TDE candidates. Instead, a simple model where the SMBH mass function is multiplied by a constant TDE rate (orange dashed line), and that takes into account the suppression due to direct captures, provides a better description of the observations (black solid line)

Improving the statistics of centrally located SNe requires uniform, higher spatial resolution surveys. Arguably the highest spatial resolution transient survey currently running is *Gaia*, with a typical astrometric accuracy of a few tenths of an arcsecond. Blagorodnova et al. (2016) show that a transient fainter than $G = 16$ mag (roughly equivalent to $V = 16$) can be resolved by *Gaia* if it is more than 0.2 arcsec away from the bulge of the galaxy. Within this 0.2 arcsec volume, they find that SNe and TDEs occur in roughly equal numbers. Further improvements in *Gaia* astrometry may push this ratio in favour of TDEs (see also Kostrzewa-Rutkowska et al. 2018 for a discussion on nuclear transients in *Gaia*).

Connections between extreme SNe and TDE claims (e.g., Komossa et al. 2009; Drake et al. 2011) are questioned by Gezari et al. (2009), see Sect. 4 above. Nevertheless, unusual conditions in the galactic core, including a dense interstellar medium in the circumnuclear region of a starved/dormant AGN, may boost peculiar SNe rates there. Gas confinement may alter SN shock physics and radiative efficiency, potentially producing an abnormally shallow light curve (Saxton et al. 2018). A larger and more representative census of nuclear SNe, as well as improved models, is needed to resolve this issue.

7.2 Host Galaxy SMBH and Stellar Masses

TDEs prefer hosts with SMBH masses $M_{BH} < 10^8 M_\odot$ (Wevers et al. 2017, 2019b; Mockler et al. 2019). This is not surprising, given that the tidal radius should be outside the Schwarzschild radius for TDEs to be observable. TDEs and AGN can be distinguished statistically using differences in their black hole mass functions (van Velzen 2018). The expected volumetric rate of AGN flares, assuming that the flare reoccurrence time scales linearly with M_{BH}, does not match the observed volumetric rate of observed TDE candidates (Fig. 16). Instead, a simple model where the SMBH mass function is multiplied by a constant TDE rate, and that takes into account the suppression due to direct captures, is more successful. van Velzen (2018) argue that the strong suppression of the volumetric rate for $M_{BH} > 10^8 M_\odot$ can only be explained by the TDE scenario.

At least some AGN that arise from lower mass SMBHs may be distinguished from the TDE population by other signatures. For example, AGN driven by SMBHs with
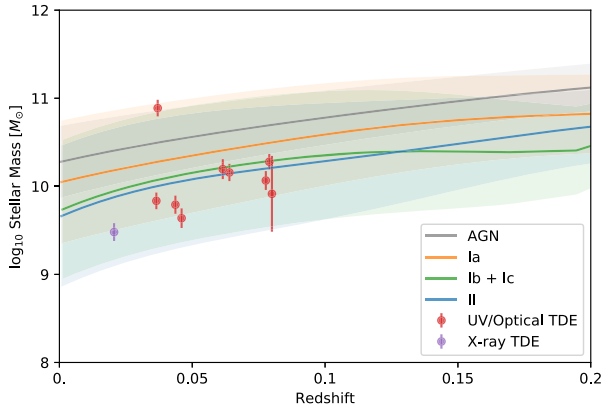
Fig. 17 Host galaxy stellar masses versus redshift for UV/optical (red points) and X-ray (purple point) TDEs, SNe (orange, green, and blue mean lines and $\pm 1\sigma$ bands), and AGN (grey mean line and $\pm 1\sigma$ band). Data are compiled from the transient-host catalogue of Qin et al. (in prep.). The high outlier event, AT2018dyk (ZTF18aajupnt), is listed as an optical/UV TDE in the French et al. 2020, Host Galaxies Chapter. For its stellar velocity dispersion of $121 \pm 3.8 \, \mathrm{km\,s^{-1}}$ (SDSS DR8 spectral catalogue; Aihara et al. 2011), its SMBH mass would be roughly $1.6 \times 10^7 \, M_\odot$ (from the scaling relation in McConnell et al. 2011), only marginally higher than typical of other TDE host galaxies (Wevers et al. 2019b). Frederick et al. (2019) alternately classify this source as a rapidly brightening LINER, whose later UV and optical spectra reveal a NLSy1 with strong coronal lines. The stellar masses of these TDE host galaxies are, on average, 0.74 dex ($\sim 1.8\sigma$) below those of AGN hosts at the same redshift

$10^6 \lesssim (M_{\mathrm{BH}}/M_\odot) \lesssim$ few $\times 10^7$ often produce relatively narrow Balmer lines (FWHM $\sim$ 1200–2000 $\mathrm{km\,s^{-1}}$) and thus are classified as NLSy1s. Such optical spectra differ from what is seen in most (optical) TDE candidates, whose lines are much broader ($\gtrsim 15{,}000 \, \mathrm{km\,s^{-1}}$). Because the He II $\lambda 4686$ line width is similar to those of the Balmer lines in AGN, it would be considerably more narrow than in TDEs.

By extension, the host galaxies of TDEs and AGN might be expected to have different stellar mass distributions. Data for TDE, AGN, and SNe hosts suggest that TDE host stellar masses tend to be smaller than those of AGN (Fig. 17). This offset is apparent if we consider the TDEs that satisfy many of the criteria laid out in this chapter and whose hosts have known stellar masses, i.e., the TDEs with broad optical H and He emission lines and objects with the most robust classification of "X-ray" TDEs by Auchettl et al. (2017), as in the French et al. 2020, Host Galaxies Chapter.

Furthermore, when the host properties of X-ray TDE candidates are grouped by the strength of the TDE claim (French et al. 2020, Host Galaxies Chapter), the least certain TDEs (those classified as "possible" TDEs by Auchettl et al. 2017) have on average higher SMBH masses and brighter host galaxy absolute magnitudes than "likely" or "X-ray" TDEs. While robust conclusions are limited by the small sample sizes, this result suggests that the "possible" TDEs are a different population, e.g., misidentified AGN flares, which tend to in-habit more massive and brighter host galaxies. For such flares, the lack of high quality data leads not only to the "possible" TDE label, but also makes them appear similar to TDEs.

7.3 Other Host Galaxy Properties

In addition to SMBH mass (and, by correlation, total stellar mass), other host properties can be used to distinguish TDEs statistically. TDEs prefer hosts with unusual, A-star domi-

nated spectra, i.e., quiescent, Balmer-strong (QBS) galaxies and the subpopulation of post-starburst (PSB or "E+A") galaxies (Arcavi et al. 2014; French et al. 2016; Graur et al. 2018; Law-Smith et al. 2017; see also the French et al. 2020, Host Galaxies Chapter). The quiescent galaxies common among TDE hosts generally lack strong Hα emission, although several show broad emission lines indicative of Type 1 AGN. A higher fraction of TDE hosts exhibit weak, narrow emission lines, with line ratios indicating ionisation from sources other than star formation. Could the observed TDE population arise from the tail end of Type 2 AGN variability? We address this question here statistically.

The recent star formation histories of TDE host galaxies are different on average than Type 2 Seyfert or LINER AGN. For galaxies in the SDSS main spectroscopic sample that 1) have stellar masses typical of TDE host galaxies ($\log(M_\star/M_\odot) \simeq 9.5$–$10.5$) and 2) have all four emission lines required for AGN classification on the BPT diagram (Baldwin et al. 1981), 92% are star forming, 5% are Seyferts, and 3% are LINERs, according to the Kauffmann et al. (2003) criteria. While between 36–75% of TDE candidates with broad H/He lines are found in QBS galaxies, only 9% of Seyferts and 17% of LINERs are. If TDEs were the tail end of the Type 2 AGN LINER or Seyfert distributions, we would expect that 9–17% of the host galaxies were QBS galaxies, instead of 36–75%. Thus, it is unlikely that most of the observed broad H/He line TDEs are caused by the tail end of normal Type 2 AGN variability.

Furthermore, many galaxies with LINER-like spectra maybe be ionised by sources other than low-luminosity AGN, weakening the possibility that the observed TDE population is caused by extreme Type 2 AGN variability. Many LINER-like galaxies identified using the BPT diagram could be ionised by merger-induced shocks (Rich et al. 2015) or post-AGB stars (Yan and Blanton 2012). Both of these possible ionisation sources are expected to occur during the QBS or PSB stage, so the proportion of QBS and PSB galaxies hosting a true low-luminosity AGN will be lower than that inferred from the BPT diagram alone.

The host galaxies of the main optical and X-ray TDE classes are also distinct from those of core-collapse (CC) SNe. CC SNe originate from massive stars and thus are found almost exclusively in star forming regions. Star formation mostly ended more than ~ 100 Myr ago in QBS galaxies, the favoured hosts of TDEs, so massive stars, and thus CC SNe, in QBS galaxies are unlikely.

8 Conclusions and the Future

While TDE classification remains ambiguous—any single observed property may be found in other types of transients—a constellation of unusual features like those cited above, consistency with rough expectations from TDE theory, and the statistics of the transient and host galaxy populations argue that at least some candidates do in fact arise from stars tidally disrupted by SMBHs. The tallies of potentially distinguishing features included in this chapter are not meant to be rules, but initial guidelines, for these early days of TDE detection. In the RubinObs/LSST, SDSS-V, and *eROSITA* era, new, more extreme types of AGN and other transients will be discovered that are likely to cast doubt on some current TDE claims and to further complicate future TDE classifications. Yet, over the same period, thousands of new TDE candidates, as well as improvements to theoretical models of stellar disruption and disk accretion by SMBHs, will help us define any unique combinations of TDE signatures.

Some of the key outstanding questions and future needs are:

- Are TDEs are significantly less absorbed compared to AGN or is this difference a selection bias?

- Why do the X-ray spectra of some thermal-dominated TDEs harden as they evolve, while others do not?
- What is the physical driver of the hyper-variable and "changing-look" AGN now detected in time-domain surveys? This question is relevant here because flares from specific changing-look AGN (e.g., SDSS J015957.64+003310.5; LaMassa et al. 2015) have been attributed to the tidal disruption of a star around a previously active SMBH (Merloni et al. 2015). On the other hand, changing-look AGN may just be extreme examples of regular, continuous AGN variability. Thus, understanding the demographics and drivers of both changing-look and hyper-variable AGN may help to determine characteristics that distinguish them from TDEs. A crucial first step would be a large, fair census of such objects.
- What other kinds of flares in persistent AGN are out there and how are they related to TDEs?
- What signatures can distinguish between AGN flares due to variability in a pre-existing accretion disk and those due to TDEs?
- Are TDEs within pre-existing AGN more common than those around dormant SMBHs, suggesting a link between AGN and TDEs or similarities in the conditions that produce them?
- What does the detection of Bowen fluorescence lines, indicative of extreme UV radiation fields, in many TDE candidates and in flaring AGN tell us about the physical links between AGN and TDEs?
- To strengthen the TDE interpretation, it is critical to find additional examples of one-off events like ASASSN-15lh. If similar sources all lie in the host galaxy centres, then the case for TDEs is stronger. Otherwise, one example detected off-nucleus would suggest a new kind of superluminous SN.
- Are there other potential TDE impostors, such as stellar collisions, "micro-TDEs," or circumbinary flares, that occur more frequently than TDEs in quiescent, Balmer-strong galaxies? Or in the "post-starburst" subclass of these galaxies?
- Do any known SNe types or other potential TDE impostors occur more frequently than TDEs in galactic nuclei?
- What is the relationship between TDE claims and the high proportion of LINERs also found in post-starburst galaxies?

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