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Review

Tidal disruption of stars by supermassive black holes: Status of observations

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ABSTRACT

Stars in the immediate vicinity of supermassive black holes (SMBHs) can be ripped apart by the tidal forces of the black hole. The subsequent accretion of the stellar material causes a spectacular flare of electromagnetic radiation. Here, we provide a review of the observations of tidal disruption events (TDEs), with an emphasis on the important contributions of *Swift* to this field. TDEs represent a new probe of matter under strong gravity, and have opened up a new window into studying accretion physics under extreme conditions. The events probe relativistic effects, provide a new means of measuring black hole spin, and represent signposts of intermediate-mass BHs, binary BHs and recoiling BHs. Luminous, high-amplitude X-ray flares, matching key predictions of the tidal disruption scenario, have first been discovered with *ROSAT*, and more recently with other missions and in other wavebands. The *Swift* discovery of two γ-ray emitting, jetted TDEs, never seen before, has provided us with a unique probe of the early phases of jet formation and evolution, and Swift J1644+75 has the best covered lightcurve of any TDE to date. Further, *Swift* has made important contributions in providing well-covered lightcurves of TDEs discovered with other instruments, setting constraints on the physics that govern the TDE evolution, and including the discovery of the first candidate binary SMBH identified from a TDE lightcurve.

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1. Introduction

The tidal disruption of stars is an inevitable consequence of the presence of supermassive black holes (SMBHs) at the cores of galaxies. Stars in close approach can be ripped apart by the tidal forces of the SMBH. A significant fraction of the stellar material will subsequently be accreted, producing a luminous flare of electromagnetic radiation.

The occurrence of TDEs was first predicted based on theoretical considerations in the seventies. At that time, many important theoretical foundations were laid, and first ideas emerged, on the relevance and usage of TDEs in astrophysical context (Hills, 1975; Frank and Rees, 1976; Young et al., 1977; Kato and Hoshi, 1978; Gurzadian and Ozernoi, 1979; Carter and Luminet, 1982; Luminet and Marck, 1985; Rees, 1988). Questions which were raised included: Do TDEs provide a fuel source for quasars? How does the occurrence of TDEs constrain the presence of an SMBH at our galactic center? Can extreme TDEs explain variants of gamma-ray bursts (GRBs)? Are TDEs a unique signpost of the presence of dormant SMBHs at the cores of inactive galaxies?

Events were discovered in the nineties in form of luminous, soft X-ray outbursts from otherwise quiescent galaxies during the *ROSAT* all-sky survey, and have more recently been found with other X-ray missions, and at longer wavelengths. The *Swift* mission has been a game changer in this field. Its discovery of the first TDE which launched a relativistic jet, Swift J1644+57, has triggered many theoretical studies on the formation of radio jets, and Swift J1644+57 has now the best-covered lightcurve of any TDE to date. Further, *Swift* has been used for follow-ups of TDEs discovered by other missions, providing excellent lightcurves and contributing to the discovery of the first candidate binary SMBH in a quiescent galaxy.

A star is disrupted, once the tidal forces of the SMBH exceed the self-gravity of the star (Hills, 1975). The distance at which this happens, the tidal radius, is given by

$$r_{\rm t} \simeq 7 \times 10^{12} \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{\frac{1}{3}} \left(\frac{M_*}{M_\odot}\right)^{-\frac{1}{3}} \frac{r_*}{r_\odot}\ {\rm cm}\,. \tag{1}$$

A fraction of the stellar material will be on unbound orbits and escape, while the rest will eventually be accreted (Fig. 1). The events appear as luminous transients. Their emission peaks in the UV or soft X-rays, declining on the timescale of months to years (e.g., Rees, 1990; Evans and Kochanek, 1989; Cannizzo et al., 1990). Because tidal radius and Schwarzschild radius depend differently on

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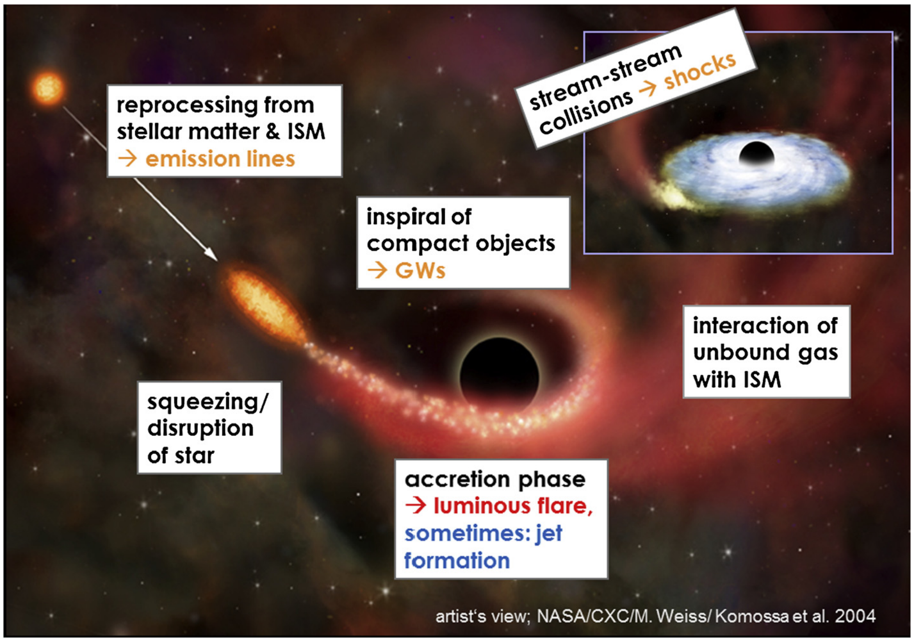


Fig. 1. Sites and sources of radiation during the evolution of a TDE. In most cases, the accretion phase is the most luminous electromagnetic phase. Only some TDEs launch radio jets.

BH mass, solar type stars are swallowed whole for SMBH masses exceeding $\sim 10^8 M_\odot$ (SMBH spin can raise this limit; Beloborodov et al., 1992). White dwarfs can be tidally disrupted for SMBH masses below $\sim 10^5 M_\odot$.

Computations of the stellar evolution, including the early stages of stellar deformation, the actual disruption, accretion and ejection of material, the development of a disk wind, and the evolution and late stages of the accretion phase, and for different types of stars, are very challenging. Recent state of the art modeling has addressed the different stages of TDE evolution under various conditions (for the most recent results, see, e.g., Bonnerot et al., submitted for publication; Guillochon and Ramirez-Ruiz, submitted for publication; Hayasaki et al., submitted for publication; Miller, submitted for publication; Piran et al., 2015; Shiokawa et al., 2015, and the references therein).

Other recent studies have addressed the disruption rates for different galaxy morphologies (e.g., Brockamp et al., 2011; Vasiliev, 2014; Stone and Metzger, submitted for publication; Zhong et al., 2014), and for recoiling and binary SMBHs (e.g., Komossa and Merritt, 2008; Chen et al., 2009, 2011; Stone and Loeb, 2011, 2012a; Li et al., 2012; Liu and Chen, 2013) and spinning BHs (Kesden, 2012). These have shown that rates are strongly boosted in some phases of binary SMBH evolution and the early phase of SMBH recoil, and that rates strongly depend on BH spin for the most massive BHs ($M > 10^8 M_\odot$). Tidally disrupted stars will also produce a gravitational wave signal along with the electromagnetic emission (e.g., East, 2014, and the references therein).

There is now increasing evidence that SMBHs reside at the centers of many massive galaxies (review by Graham, 2015). TDEs likely significantly contributed to growing SMBHs at low masses ($M_{\rm BH} < 10^{5-6} M_\odot$; Freitag and Benz, 2002), while stars swallowed whole may have contributed to SMBH growth at high masses (Zhao et al., 2002). One initial idea was to use TDE flares as tracers of dormant SMBHs in quiescent galaxies (e.g., Rees, 1988). This will continue to be an important topic in the future, since the luminous accretion flares reach out to large cosmic distances, and TDEs will be detected in large numbers in future transient surveys (Section 8). In addition, many other applications have been suggested, making use of the characteristic TDE properties and rates:

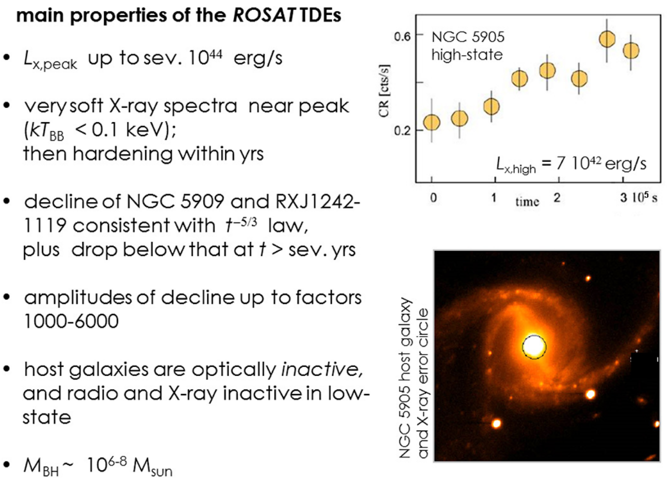
- In X-rays, TDEs probe relativistic effects (via emission-line profiles or precession effects in the Kerr metric) and the extremes of accretion physics at high rates and near the last stable orbit, and provide us with a new means of measuring BH spin.
- Jetted TDEs provide new insight into the formation and early evolution of radio jets, and may shed new light on related issues like the cause of the radio-loud radio-quiet dichotomy of active galactic nuclei (AGN).
- TDEs, once detected in large numbers, will unveil the population of IMBHs in the universe.
- TDE rates depend on, and therefore trace, stellar dynamics in galaxy cores on spatial scales which cannot be resolved directly.
- TDEs are signposts of binary SMBHs and recoiling BHs, because their rates are strongly enhanced under these conditions, and TDEs will occur off-nuclear if the SMBH is recoiling.
- TDEs in gas-rich environments will illuminate the circumnuclear material, so that the reprocessed emission lines and their temporal evolution provide us with an unparalleled opportunity of reverberation mapping the cores of quiescent galaxies.

Here, we present an overview of the status of observations of TDEs, highlighting the important role plaid by the *Swift* mission (Gehrels et al., 2004; Gehrels and Cannizzo, in press). An accompanying review by Lodato (in press) will focus on theoretical aspects of tidal disruption.

2. TDEs in soft X-rays (non-jetted)

2.1. *ROSAT* TDEs

The *ROSAT* observatory (Trümper, 2001) with its high sensitivity, long lifetime, all-sky coverage in its first year of operation, and soft X-ray response (0.1–2.4 keV), was well suited for the detection of TDEs. Luminous, high-amplitude X-ray flares from quiescent galaxies, matching all order-of-magnitude predictions of the tidal disruption scenario (e.g., Rees, 1990), have first been discovered during the *ROSAT* X-ray all-sky survey (RASS; Figs. 2, 3). Four main events were identified, from the galaxies NGC 5905



main properties of the *ROSAT* TDEs

- $L_{\rm x,peak}$ up to sev. 10^{44} erg/s
- very soft X-ray spectra near peak ($kT_{\rm BB}$ < 0.1 keV); then hardening within yrs
- decline of NGC 5909 and RXJ1242-1119 consistent with $t^{-5/3}$ law, plus drop below that at t > sev. yrs
- amplitudes of decline up to factors 1000-6000
- host galaxies are optically *inactive*, and radio and X-ray inactive in low-state
- $M_{\rm BH}$ ~ $10^{6\text{-}8}$ $M_{\rm sun}$

Fig. 2. Summary of the main properties of the *ROSAT* events. The figures show the rise to the highest observed state of NGC 5905 during the RASS and an image of the host galaxy.

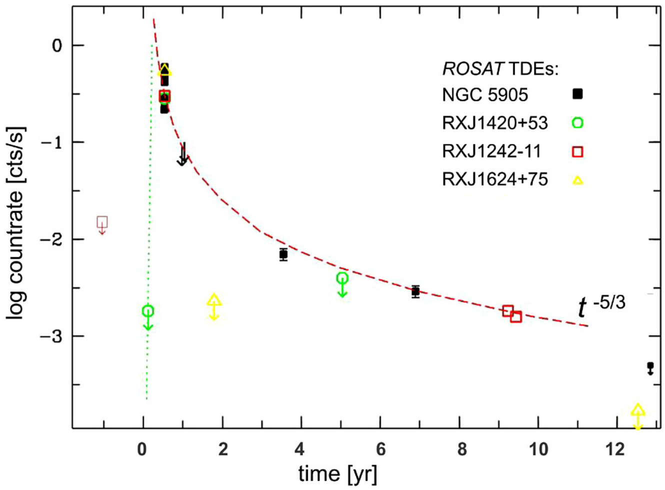


Fig. 3. Joint X-ray lightcurve of the *ROSAT* TDEs, all shifted to the same peak time. The decline is consistent with a $t^{-5/3}$ law (dashed lined). This point was first made based on the *ROSAT* data of NGC 5905 (Komossa and Bade, 1999), and later for the overall luminosity evolution of the sources displayed above (e.g., Fig. 1 of Komossa, 2004). RXJ1242-1119 shows a further drop in X-rays at late times (not shown here), deviating from the early phase decline law, implying a total amplitude of decline of a factor ~1000 (Komossa, 2005).

(Bade et al., 1996; Komossa and Bade, 1999; see also Li et al., 2002), RXJ1242-1119 (Komossa and Greiner, 1999), RXJ1624+7554 (Grupe et al., 1999), and RXJ1420+5334 (Greiner et al., 2000). Among these, NGC 5905 and RXJ1242-1119 are the best-covered events in terms of their *long-term* X-ray lightcurves, spanning time intervals of more than a decade, with amplitudes of decline *larger than a factor of 1000* (Komossa et al., 2004; Halpern et al., 2004; Komossa, 2005).

NGC 5905 was first noticed due to its luminous, soft ($kT = 0.06$ keV) X-ray emission with peak luminosity in the soft X-ray band of $L_{\rm x,peak} = 7 \times 10^{42}$ erg/s during the RASS. It remained bright for at least ~5 days (the time interval its position was repeatedly scanned during the RASS) increasing in luminosity to the observed peak. X-rays then declined on the timescale of months to years (Fig. 3). Within the errors, the X-rays came from the center of this nearby barred spiral galaxy ($z = 0.011$; Fig. 2). While the X-ray spectrum was initially very soft, it had hardened significantly ($\Gamma_{\rm x} = -2.4$) 3 years later, when re-observed with *ROSAT*. The decline of its X-ray lightcurve is well consistent with the predicted $t^{-5/3}$ law, as first reported based on its *ROSAT* observations (Komossa and Bade, 1999) and confirmed with *Chandra* (Halpern et al., 2004). All observations of this event are in very good agreement with tidal disruption theory (Bade et al., 1996; Komossa and Bade, 1999).

Whenever enough data exist, the *ROSAT* events, and most of the more recent soft X-ray TDEs (next section), follow a similar trend in spectral and lightcurve evolution as NGC 5905, providing independent evidence that the same mechanism was at work in all cases.

2.2. New soft X-ray TDEs and Swift follow-ups

More recently, similar X-ray events have been detected with *Chandra* and *XMM-Newton*, based on dedicated searches or serendipitous discoveries. The *XMM-Newton* slew survey has been used to identify new bright TDEs based on a comparison with the *ROSAT* data base, and a few events have been found so far (Esquej et al., 2007, 2008; Saxton et al., 2012b). Among these, SDSSJ120136.02+300305.5 has the best-covered first-year lightcurve (Saxton et al., 2012b), based on follow-ups with *XMM-Newton* and *Swift*. Overall, the X-rays continue fading after high-state. Additional large-amplitude variability is apparent on the timescale of weeks (Fig. 4). The X-ray spectrum of SDSSJ120136.02+300305.5, observed with *XMM-Newton* weeks and months after high-state is very soft (no photons detected beyond 2–3 keV), but is not well fit with black-body emission. It is consistent with a broken powerlaw or a Bremsstrahlung-like spectral shape.

A few TDEs were identified in clusters of galaxies (Cappelluti et al., 2009; Maksym et al., 2010, 2013; Donato et al., 2014). The most likely counterpart of the source WINGS J1348 in Abell 1795 is a dwarf galaxy, and the disrupting black hole is of relatively low mass, $M_{\rm BH} < 10^6 M_\odot$ (Maksym et al., 2013, 2014a; Donato et al., 2014). A second candidate TDE hosted by a dwarf galaxy was reported by Maksym et al. (2014b).

Other events emerged through systematic searches of the *XMM-Newton* data base (Lin et al., 2011, submitted for publication) and new searches of the *ROSAT* data base (Khabibullin and Sazonov, 2014; Maksym et al., 2014b). The events cover X-ray luminosities in the range (10^{42}–several 10^{44}) erg/s, and arise in relatively nearby galaxies ($z = 0.03$–0.2) which are optically quiescent (i.e., they lack the characteristic optical narrow emission lines of AGN). The *Swift* mission has been essential in providing rapid follow-ups of several of these events, confirming the fading X-rays, and providing tight constraints on the luminosity evolution.

Overall, the salient properties of the soft X-ray TDEs detected with *ROSAT*, *XMM-Newton* and *Chandra* can be summarized as follows:

- Peak luminosities are large, up to several 10^{44} erg/s in the soft X-ray band.
- Amplitudes of decline reach factors up to 1000–6000 (the *ROSAT* events), more than a decade after the observed high-states.
- X-ray spectra are very soft during the high-states ($kT_{\rm BB} \sim 0.04$–0.1 keV), followed by a spectral hardening on the time scale of years.
- Host galaxies show essentially no evidence for *permanent* activity as it is seen in AGN. Years after the flare (and before, when data exist), the galaxies are optically inactive, radio inactive, and X-ray inactive.
- X-ray lightcurves decline on the timescale of months–years, and are overall consistent with the law $L \propto t^{-5/3}$ predicted by the fall-back model of tidal disruption theory.

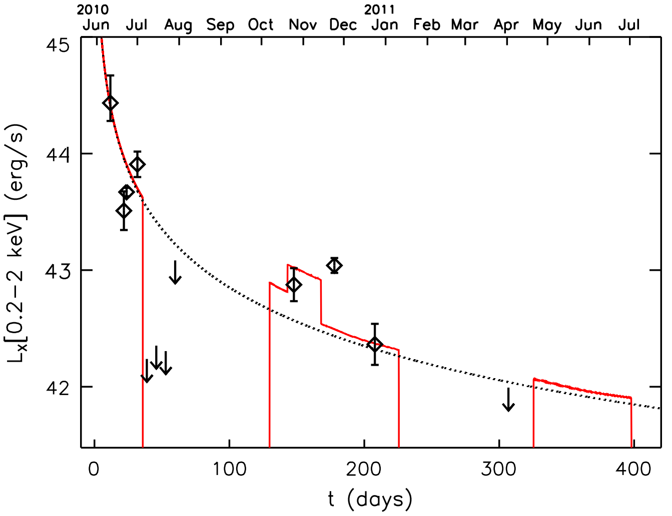


Fig. 4. *Swift* and *XMM-Newton* X-ray lightcurve of the X-ray outburst from SDSSJ120136.02+300305.5, and predictions from the SMBBH model of Liu et al. (2014, red solid line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- SMBH masses (derived from applying scaling relations or multi-wavelength correlations) are mostly on the order of 10^6–$10^8 M_\odot$.
- Only a small amount of the stellar material needed to be accreted to power the observed emission, typically $<10\% \ M_\odot$.

2.3. A candidate binary SMBH

The lightcurve of the TDE from SDSSJ120136.02+300305.5 (Section 2.2, Fig. 4) does show the overall downward trend expected after tidal disruption. However, one month after the peak, the X-ray emission suddenly dropped by a factor of >50 within a week and the source was no longer detected by *Swift*. X-rays re-appeared after 115 d, and then dropped a second time.

If the intermittence of the X-ray emission was due to absorption, the first disappearance in X-rays would require a huge column density of gas of order $N_{\rm H} > 10^{23}$ cm^{-2}. While in AGN, a broad-line cloud could be the source of such absorption, the optical spectrum of SDSSJ120136.02+300305.5 is that of a non-active galaxy, without any detectable emission lines neither before nor after the outburst. The chances of molecular clouds in the very core repeatedly crossing our line-of-sight toward the X-ray source are therefore very low. Further, no jet was launched by this TDE, since no radio emission was detected at all (Saxton et al., 2012b).

However, the characteristic intermittence and recovery of the lightcurve of SDSSJ120136.02+300305.5 is reminiscent of predictions by Liu et al. (2009), who computed TDE lightcurves in binary SMBHs. In that case, the second SMBH acts as a perturber and temporarily interrupts the accretion stream on the primary. Simulations by Liu et al. (2014) have shown, that the lightcurve of SDSSJ120136.02+300305.5 is well consistent with a binary SMBH model (Fig. 4) with a primary mass of $10^6 M_\odot$, a mass ratio $q \sim 0.1$ and semi-major axis of 0.6 milli-pc (mpc).

This is the first supermassive binary BH (SMBBH) candidate identified in a non-active host galaxy, and the one with the most compact orbit among the known SMBBH candidates (review by Komossa and Zensus, in press). It has overcome the "final parsec problem" (e.g., Colpi, 2014). Upon coalescence, it will be a strong source of gravitational wave emission in the sensitivity range of space-based gravitational wave detectors. If significant numbers of SMBBHs exist at the cores of non-active galaxies, we expect to see more such events in *Swift* lightcurves of TDEs. A good lightcurve coverage is essential for constraining the system parameters.

3. UV and optical flares

The *Galaxy Evolution Explorer* (*GALEX*; Martin et al., 2005) mission performed the first sky survey in the UV from space, and was well suited for a search for TDEs at UV wavelengths. Three events were first identified in the UV. The first one was detected in the *GALEX* Groth field and showed UV variability by a factor of a few (Gezari et al., 2006). An elliptical galaxy at redshift $z = 0.370$ was identified as host. Its spectrum shows only faint emission from [OIII] and is dominated by stellar absorption features. Two more events were identified with *GALEX* (Gezari et al., 2008, 2009; our Table 1).

In the optical bandpass, several photometric sky surveys have become online recently, performing wide-field transient surveys at high cadence [e.g., PTF (Law et al., 2009), Pan-STARRS (Kaiser et al., 2002), and for selected areas also SDSS (York et al., 2000)]. These have found several TDE candidates based on their optical variability, with lightcurves (or spectra) which look different from those of known supernovae.

The first event identified optically was from SDSS, associated with the galaxy SDSSJ095209.56+214313.3 (Komossa et al., 2008). It shows only mild optical variability of ∼1 mag, but was noticed for its transient optical emission lines which imply a luminous high-energy flare (Section 4). Van Velzen et al. (2011a) performed a search for optical flares using the SDSS stripe 82 data base, and presented two probable TDEs, optically variable by factors 2–2.5. One of them showed evidence for variable broad-line emission. Further optical flares, some followed up with *Swift UVOT*, were reported by Cenko et al. (2012a), Gezari et al. (2012), Holoien et al. (2014), Vinko et al. (2015), Arcavi et al. (2014), and Chornock et al. (2014). Several of them come with variable optical emission lines (further discussed in Section 4), while the spectrum of PS1-11af (Chornock et al., 2014) is featureless except for two deep UV absorption features.

Overall, the UV and optical events have spectral energy distributions that are peaked at much lower temperatures ($T_{\rm bb} \approx 10^4$ K) than the X-ray events ($T_{\rm bb} \approx 10^5$ K), and the majority of the low-temperature events did not have detectable X-ray emission (even though for the higher-redshift UV sources limits on X-ray emission, including in low-state, are not as tight as those for the more nearby *ROSAT*, *Chandra* and *XMM-Newton* X-ray events).

4. Emission-line transients

When traveling through any gaseous material of the galaxy core, the bright EUV-X-ray continuum of a TDE is reprocessed into emission lines. These emission lines provide us a with a powerful new opportunity of measuring the physical conditions in the circum-nuclear material.

When the luminous electromagnetic radiation travels across the galaxy core, it will photoionize any circum-nuclear material (Rees, 1998; Ulmer, 1999) and the tidal debris itself (Bogdanovic et al., 2004; Strubbe and Quataert, 2011) and is reprocessed into line radiation. This emission-line signal enables us to perform reverberation mapping of any gaseous material in the galaxy core, including, in principle, high-density gas like the broad-line region (if present), the molecular torus, and the interstellar medium. We will also be able to address, which of these regions are permanently present in non-active galaxies. The emission-line fluxes, line widths, line shifts, and their evolution with time, tightly constrain the amount, density, composition, dynamics and geometry of the circum-nuclear material.

Recently, large optical spectroscopic surveys (SDSS), and follow-ups of sources identified in photometric transient surveys (PanSTARRS, PTF, ASAS-SN) have enabled the discovery of several well-observed cases of transient optical emission lines, arising

Table 1
Candidate TDEs identified from X-ray, UV and optical observations. [Only sources are listed which showed high-amplitude variability (largest in X-rays, and at least a factor of 2 in the optical and UV), along with a good optical galaxy counterpart for which follow-up spectroscopy confirmed an essentially inactive host galaxy. Most of the listed sources, especially those with long-term coverage, are also quiescent in terms of their low-state X-ray emission and absence of radio emission. Also note that several events were detected in more than one waveband; the sorting in the table is according to the waveband in which the event was initially identified.]

Source name	Redshift	Discovery mission	Reference
		Soft X-ray events	
NGC 5905	0.011	*ROSAT*	Bade et al. (1996), Komossa and Bade (1999)
RX J1242-1119	0.050	*ROSAT*	Komossa and Greiner (1999)
RX J1624+7554	0.064	*ROSAT*	Grupe et al. (1999)
RX J1420+5334	0.147	*ROSAT*	Greiner et al. (2000)
NGC 3599	0.003	*XMM-Newton*	Esquej et al. (2007, 2008)
SDSS J1323+4827	0.087	*XMM-Newton*	Esquej et al. (2007, 2008)
TDXF 1347-3254	0.037	*ROSAT*	Cappelluti et al. (2009)
SDSS J1311-0123	0.195	*Chandra*	Maksym et al. (2010)
2XMMi 1847-6317	0.035	*XMM-Newton*	Lin et al. (2011)
SDSS J1201+3003	0.146	*XMM-Newton*	Saxton et al. (2012b)
WINGS J1348	0.062	*Chandra*	Maksym et al. (2013), Donato et al. (2014)
RBS1032	0.026	*ROSAT*	Maksym et al. (2014b), Khabibullin and Sazonov (2014)
3XMM J1521+0749	0.179	*XMM-Newton*	Lin et al. (submitted for publication)
		Hard X-ray events	
Swift J1644+57	0.353	*Swift*	Bloom et al. (2011), Burrows et al. (2011) Levan et al. (2011), Zauderer et al. (2011)
Swift J2058+0516	1.186	*Swift*	Cenko et al. (2012b)
		UV events	
J1419+5252	0.370	*GALEX*	Gezari et al. (2006)
J0225-0432	0.326	*GALEX*	Gezari et al. (2008)
J2331+0017	0.186	*GALEX*	Gezari et al. (2009)
		Optical events	
SDSS J0952+2143[a]	0.079	SDSS	Komossa et al. (2008)
SDSS J0748+4712[a]	0.062	SDSS	Wang et al. (2011)
SDSS J2342+0106	0.136	SDSS	Van Velzen et al. (2011a)
SDSS J2323-0108	0.251	SDSS	
PTF 10iya	0.224	PTF	Cenko et al. (2012a)
SDSS J1342+0530[a]	0.034	SDSS	Wang et al. (2012)
SDSS J1350+2916[a]	0.078	SDSS	
PS1-10jh	0.170	Pan-STARRS	Gezari et al. (2012)
ASASSN-14ae	0.044	ASAS-SN	Holoien et al. (2014)
PTF 09ge	0.064	PTF	Arcavi et al. (2014)
PTF 09axc[b]	0.115	PTF	
PTF 09djl	0.184	PTF	
PTF 10nuj[c]	0.132	PTF	
PTF 11glr[c]	0.207	PTF	
PS1-11af	0.405	Pan-STARRS	Chornock et al. (2014)

[a] Identified by their transient emission lines.

[b] Luminous X-ray emission of 7×10^{42} erg/s was detected with *Swift* in 2014 (Arcavi et al., 2014) well within the regime of Seyfert galaxies, and therefore either indicates long-lived AGN activity, or is still related to the optical flare.

[c] The positions of these two events are consistent with an off-center or a central location.

from otherwise quiescent galaxies (as judged from their low-ionization emission-line ratios; or from the absence of any narrow emission lines). All of them exhibit bright, broad, fading emission from helium and/or hydrogen (Komossa et al., 2008, 2009; Wang et al., 2011, 2012; van Velzen et al., 2011a; Gezari et al., 2012; Gaskell and Rojas Lobos, 2014; Holoien et al., 2014; Arcavi et al., 2014), while some of them additionally show transient super-strong iron coronal lines up to ionization stages of Fe^{13+} including transitions of [FeVII], [FeX], and [FeXIV] (Komossa et al., 2008, 2009; Wang et al., 2011, 2012; Yang et al., 2013). All events have been interpreted as candidate TDEs.[1]

Luminous, transient high-ionization lines with ionization potential in the soft X-ray regime implied the presence of a high-amplitude high-energy outburst (even though simultaneous X-ray observations did not exist). The most luminous coronal lines are those from SDSSJ095209.56+214313.3 (Fig. 5). The highest ionization lines have faded by a factor of >10 several years after high-state and are no longer detectable. The broad Hα line is asymmetric and comes with an initial redshift of 600 km/s, and additional multi-peaked narrow components are present (Komossa et al., 2008). The highest-ionization lines, as well as broad H and He lines, continue fading over several years, while the lower-ionization lines like [OIII] increase in strength (Komossa et al., 2009; Wang et al., 2012; Yang et al., 2013), consistent with light travel time effects, i.e., flare emission reaching more extended regions of gaseous material/ISM as time goes by.

The broad emission lines from H and He may arise from the tidal debris itself which forms the accretion disk (see Guillochon et al., 2014, Bogdanovic et al., 2014, and Gaskell and Rojas Lobos, 2014 for models of PS1-10jh), while line emission from the unbound stellar streams is expected to be very faint. Repeated spectral coverage shortly after peak is available for two of the events identified in the PTF archive (Arcavi et al., 2014), and one event identified in the ASAS-SN survey (Holoien et al., 2014) along with optical lightcurves. The Balmer emission lines show complex, variable profiles with kinematic shifts as high as several 1000 km/s.

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[1] All of these events are consistent with arising from the galaxy cores, and look significantly different from known supernovae (spectra and/or lightcurves). Nonetheless, an SN origin cannot be ruled out yet, and SNe exploding in the dense, gas-rich core region of galaxies may well look different from other SNe (see the discussion by Komossa et al., 2009, Drake et al., 2011, and Arcavi et al., 2014). The high inferred X-ray luminosities from the strong coronal lines place particularly tight constraints on any supernova origin (Komossa et al., 2009).

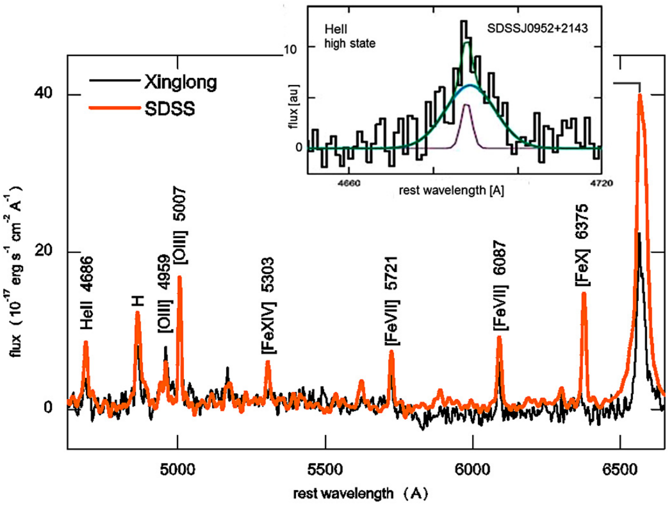
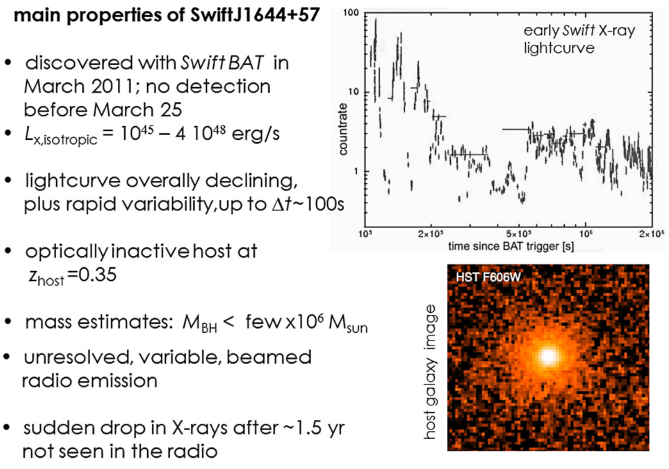


Fig. 5. Strong and transient Balmer and high-ionization emission lines in the optical spectrum of SDSSJ095209.56+214313.3 (note that the resolution of the SDSS spectrum was decreased for this plot, to match that of the *Xinglong* spectrum). The inset shows a zoom on HeII λ4686. While the highest-ionization iron lines were very bright initially (SDSS spectrum, red), they were much fainter in a *Xinglong* spectrum (black) taken several years later (Komossa et al., 2008; see Wang et al., 2012 for several more cases). For examples which lack the narrow, high-ionization lines, but still show bright and broad emission of Balmer lines and/or HeII, see Wang et al. (2011) (their Fig. 1), Gezari et al. (2012) (their Fig. 1), and Arcavi et al. (2014) (their Fig. 4). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



main properties of SwiftJ1644+57

- discovered with *Swift BAT* in March 2011; no detection before March 25
- $L_{\mathrm{x,isotropic}} = 10^{45} - 4\ 10^{48}$ erg/s
- lightcurve overally declining, plus rapid variability, up to $\Delta t \sim 100$s
- optically inactive host at $z_{\mathrm{host}} = 0.35$
- mass estimates: $M_{\mathrm{BH}} <$ few x10^6 M_{sun}
- unresolved, variable, beamed radio emission
- sudden drop in X-rays after ~1.5 yr not seen in the radio

Fig. 6. Summary of some main observational properties of Swift J1644+75. The panels show the early-phase X-ray lightcurve (see Burrows et al., 2011) and the *HST* optical image of the host galaxy from Levan et al. (2011).

Likely, all events are related, and those with fainter broad lines present a later stage in evolution (while strong narrow high-ionization lines only appear in gas-rich environments). A future test of the TDE interpretation will consist of searching for similar events at off-nuclear locations. While recoiling SMBHs and ongoing galaxy mergers will produce off-nuclear TDEs (Komossa and Merritt, 2008; Liu and Chen, 2013), these events would be rare in the local universe, and the vast majority of nearby TDEs should therefore arise from the very cores of their host galaxies.

5. *Swift* discovery of jetted TDEs

5.1. Observations of Swift J164449.3+573451

A new chapter in the study of TDEs was opened when *Swift* detected the unique transient GRB110328A/Swift J164449.3+573451 (Swift J1644+57 hereafter). It was first noticed when it triggered the *Swift* Burst Alert Telescope (BAT) in March 2011 (Cummings et al., 2011), and initially shared similarities with a GRB. However, the X-rays by far did not fade as quickly as expected for GRBs.

The rapid rise, huge X-ray peak luminosity, long duration, compact and variable associated radio emission, and optically inactive host galaxy all contributed to the interpretation of this event as the launch of a powerful jet following the tidal disruption of a star (Bloom et al., 2011; Burrows et al., 2011; Zauderer et al., 2011; Levan et al., 2011).

The early evolution of the lightcurve is characterized by recurrent high-amplitude flares with (isotropic) peak luminosities exceeding 10^{48} erg/s (Burrows et al., 2011). After the first few days, the lightcurve shows an overall decline (Figs. 6, 7), but continues to be complex and highly variable, with variability timescales as short as ∼100 s.

Optical imaging and spectroscopy revealed the host galaxy at redshift $z = 0.353$ (Levan et al., 2011). The optical emission lines imply that the host is not an AGN, but an HII-type galaxy. Variable emission was also detected in the NIR (not in the optical; likely due to the excess extinction seen in the optical spectrum). Various estimates of the SMBH mass, based on scaling relations or the most rapid variability timescale all give $M_{\mathrm{BH}} < 10^7 M_{\odot}$.

Swift J1644+57 was also associated with bright, compact, variable radio synchrotron emission (e.g., Zauderer et al., 2011) coincident with the nucleus of the host galaxy. Radio emission was already detected during the first radio follow-up observation of Swift J1644+57 four days after the first X-ray detection with *Swift*.

Tidal disruption of a star powering a relativistic jet pointing in our direction has been the widely favored explanation of this unique event. Given the relatively low mass of the SMBH, the observed peak luminosity of Swift J1644+57 is up to a few orders of magnitude above the Eddington limit, implying that either the accretion at peak was highly super-Eddington, and/or that the emission was boosted due to a collimated relativistic jet.

A variety of follow-up observations of Swift J1644+57 have been carried out at all wavelengths (X-rays: Saxton et al., 2012a; Reis et al., 2012; Castro-Tirado et al., 2013; Zauderer et al., 2013; Gonzalez-Rodriguez, 2014; Mangano et al., in press; radio: Berger et al., 2012; Zauderer et al., 2013; Cendes et al., 2014; IR and radio polarimetry: Wiersema et al., 2012). Non-detections were reported with *VERITAS* and *MAGIC* at energies >100 GeV (Aliu et al., 2011; Aleksic et al., 2013).

In X-rays, evidence for a quasi-periodicity of 200 s was reported by Reis et al. (2012); see also Saxton et al. (2012b). Unlike the long-term X-ray lightcurve, the radio emission from Swift J1644+75 continued to rise (Berger et al., 2012; Zauderer et al., 2013; our Fig. 8). The *Swift* X-ray lightcurve of Swift J1644+57 continued declining (Fig. 7), but then showed a sudden drop at ∼500 days by a factor of ∼170; no longer detectable with *Swift* but still with *Chandra* (Zauderer et al., 2013) and *XMM-Newton* in deeper pointings (Gonzalez-Rodriguez et al., 2014). The rapid decline is not seen in the radio (Fig. 8), implying that X-ray and radio emission have different sites of origin also at late times. Zauderer et al. (2013) interpreted the drop in X-ray emission as evidence for a change in accretion mode, turning off the jet production; while the faint late-stage X-rays themselves (and the ongoing radio emission) are consistent with arising from the forward shock related to the jet.

5.2. Theory and implications

The discovery of Swift J1644+57 has triggered a large number of theoretical studies, addressing the trajectory and type of the disrupted star and mass and spin of the SMBH (Shao et al., 2011;

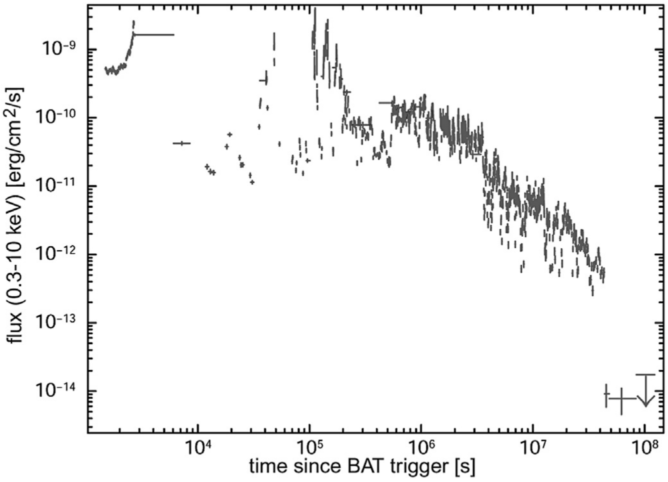


Fig. 7. *Swift* long-term lightcurve of Swift J1644+75. Data are available at www.swift.ac.uk/xrt_curves. (See also Zauderer et al., 2013, and see Mangano et al., in press for a detailed spectral and timing analysis of the whole *Swift* lightcurve.)

Miller and Gültekin, 2011; Lei and Zhang, 2011; Cannizzo et al., 2011; Krolik and Piran, 2011; Abramowicz and Liu, 2012), the nature of the radio emission and general implications for the formation of radio jets (Metzger et al., 2012; Wang and Cheng, 2012; Krolik and Piran, 2012; De Colle et al., 2012; Cao and Wang, 2012; Gao, 2012; Barniol Duran and Piran, 2013; Kumar et al., 2013; Zou et al., 2013; Tchekhovskoy et al., 2014; Wang et al., 2014; Kelley et al., 2014; Parfrey et al., 2015; Liu et al., 2015; Mimica et al., submitted for publication; see also comments by van Velzen et al., 2011b; Giannios and Metzer, 2011), the evolution of the accretion disk including effects of precession (Stone and Loeb, 2012b; Socrates, 2012; Lei et al., 2013; Kawashima et al., 2013; Coughlin and Begelman, 2014; Shen and Matzner, 2014), and a few alternative interpretations of the event (Ouyed et al., 2011; Quataert and Kasen, 2012; Woosley and Heger, 2012).

A key question which has been raised (first mentioned in application to Swift J1644+57 by Bloom et al., 2011), regards the role of magnetic fields in magnetohydrodynamic models of jet formation, and specifically the question, whether the required large-scale magnetic field is generated *in situ* in the disk, or is rather advected in with the flow. The magnetic field strength estimated for Swift J1644+57 is much higher than that of a main-sequence star, and must have then been generated locally in the disk, or requires the presence of a fossil disk.

Regarding the source of the long-term radio emission there is overall consensus that it is very likely synchrotron radiation from the shock which is formed when the jet interacts with the interstellar medium.

Another focus of attention has been the nature of the X-ray emission and its rapid variability and early epochs of high-amplitude flaring. Most models have linked it with dissipation in the inner jet (and/or effects of jet precession or nutation), and/or the forward shock, rather than directly with emission from the accretion disk.

Finally, a topic of close consideration has been the trajectory and type of the disrupted star. While several studies have assumed, or explored, the disruption of a main-sequence star, arguments have also been made in favor of the disruption of a white dwarf (Krolik and Piran, 2011), a giant star (Shao et al., 2011), or a star with a deeply plunging orbit (Cannizzo et al., 2011).

5.3. Swift J2058.4+0516

Evidence for a possible second jetted TDE discovered by *Swift* was reported by Cenko et al. (2012b). Swift J2058.4+0516 (Swift J2058+05 hereafter) exhibited a luminous, long-lived X-ray outburst with an (isotropic) peak luminosity of $L_x \approx 3 \times 10^{47}$ erg/s. Its X-ray lightcurve shows rapid variability as fast as 1000 s. The event is accompanied by strong radio emission. The likely host galaxy of Swift J2058+05 is at redshift $z = 1.185$, and is optically inactive. Because of the many similarities with Swift J1644+57, Cenko et al. suggested a similar outburst mechanism, consistent with multi-wavelength follow-up observations (Pasham et al., submitted for publication). Notably, like Swift J1644+57, the X-ray lightcurve of Swift J2058.4+0516 shows an abrupt drop (between days 200 and 300). Since the X-rays vary rapidly before the drop, an origin near the SMBH rather than in a forward shock is implied (Pasham et al., submitted for publication).

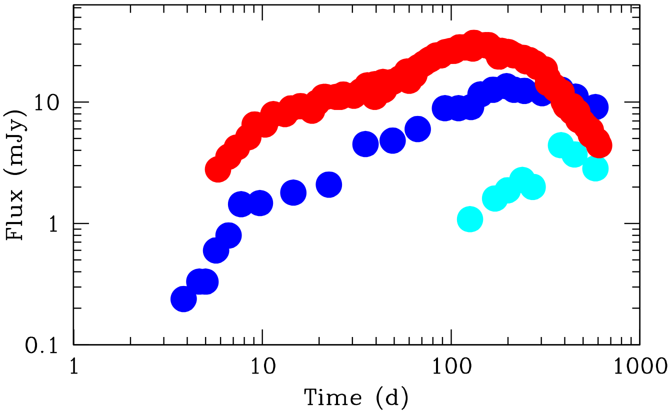


Fig. 8. Radio lightcurve (Zauderer et al., 2013) of Swift J1644+75, provided by A. Zauderer. Frequencies of 1.8 GHz (cyan), 4.9 GHz (blue) and 15 GHz (red) are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.4. Radio emission from other TDEs

The possibility that TDEs launch radio jets, came up with the detection of the first few X-ray TDEs with *ROSAT*. In order to test, whether TDEs do launch radio jets (and to exclude a peculiar mini-blazar at the galaxy core), radio follow-ups of NGC 5905 were performed with the VLA (Komossa, 2002) 6 years after the initial X-ray outburst. No radio emission was detected ($f_R < 0.15$ mJy at 8.46 GHz; see Section 2.3 of Komossa, 2002 for an extended discussion of the radio properties of NGC 5905).

More recently, deep radio follow-ups have been carried out of some of the newly identified (candidate) TDEs (e.g., van Velzen et al., 2011a; Saxton et al., 2012b; Cenko et al., 2012a; Saxton et al., 2014; Chornock et al., 2014). No radio emission was detected. Radio observations were also carried out for several of the previously known TDEs, covering time intervals of up to more than a decade (the *ROSAT* events), and years (Bower et al., 2013; van Velzen et al., 2013). Most sources were undetected with the VLA in either study, with upper limits on the flux density in the range $f_R <$ 10–200 μJy. The two exceptions (Bower et al., 2013) are the Seyfert galaxy IC 3599 [the radio emission in this AGN is most likely linked to the long-lived Seyfert activity of this galaxy, and the nature of its (repeat) X-ray flaring remains debated; e.g., Komossa et al. (in press), see our Section 7] and a source in the X-ray error circle of the *ROSAT* event RXJ1420+5334.

Jets similar to the one of Swift J1644+57 should have been detected in the deepest radio follow-ups, even if not pointed at us. Therefore, most TDEs do not launch powerful radio jets.

The fact that Swift J1644+57 does, has re-raised the question, which parameter(s) determine jet formation. In application to Swift J1644+57, BH spin or the pre-existence of a fossil disk or other mechanisms to produce a large magnetic flux to power the jet have been considered (Section 5.2).

6. TDE rates

Several approaches have been followed to estimate TDE rates from observations, making use of the *ROSAT* all-sky survey (Donley et al., 2002; Khabibullin and Sazonov, 2014), the *XMM-Newton* slew survey (Esquej et al., 2008), upper limits from *Chandra* deep fields (Luo et al., 2008), clusters of galaxies (Maksym et al., 2010), GALEX (Gezari et al., 2008), and SDSS (e.g., Wang et al., 2012; van Velzen and Farrar, 2014). All rates are in the range 10^{-4}–10^{-5}/yr/galaxy, and consistent with order-of-magnitude theoretical predictions which are on the same order (e.g., Rees, 1990; Merritt, 2009; review by Alexander, 2012).

7. TDEs in AGN?

TDEs might well occur in AGN, too, and rates are expected to be high (Karas and Subr, 2007). However, it is generally more challenging to identify TDEs in AGN because of the much lower contrast of any TDE-related accretion flare relative to the permanently bright accretion disk. Further, it is more difficult to uniquely associate any particular flare in classical AGN (i.e., galaxies which show long-lived activity in X-rays, and/or radio, and characteristic bright emission-lines from the narrow-line region) with a TDE, because processes in the long-lived accretion disk itself can potentially cause high-amplitude variability.[2] Nevertheless, a few cases of unusually high-amplitude variability of AGN have been considered in the context of a tidal disruption scenario.

7.1. The Seyfert galaxy IC 3599

(1) The Seyfert galaxy IC 3599 showed an X-ray outburst during the *ROSAT* all-sky survey, accompanied by a temporary remarkable brightening and fading of the optical emission lines (Brandt et al., 1995; Grupe et al., 1995a; Komossa and Bade, 1999). The cause of the outburst remained unknown, and high-amplitude narrow-line Seyfert 1 (NLS1) variability,[3] a disk instability, or a TDE have all been considered. IC 3599 was already known as an active galaxy before the outburst (based on its narrow emission lines like [OIII]). Recently, a second outburst of IC 3599 was discovered by *Swift* in 2010 (Komossa et al., in press; Campana et al., submitted for publication; Grupe et al., 2015). Recurrent flaring within decades is uncommon in TDE scenarios, even though not impossible, since, for instance, rates are strongly boosted under some conditions in galaxy mergers (e.g., Chen et al., 2009), and repeat tidal stripping can occur for orbiting stars surviving the first encounter. This latter possibility was explored by Campana et al. (submitted for publication), while processes related to the AGN accretion disk (and SMBBHs) where discussed by Komossa et al. (in press) and Grupe et al. (2015). Variability of similar magnitude as IC 3599 (a factor of ∼100) is rare, but has also been observed in a few other AGN,[4] likely related to processes in the long-lived AGN accretion disk (and this therefore is a likely explanation of IC 3599, too), or to absorption.

7.2. Other cases in the UV and X-rays

(2) In the UV, Renzini et al. (1995) observed faint, enhanced emission from the core of the elliptical radio galaxy NGC 4552 with *HST*, and suggested a mild accretion event from an interstellar cloud or the tidal stripping of a star; or fluctuations in the accretion rate of the very faint AGN in NGC 4552 (Cappellari et al., 1999; Renzini, 2001). The UV spike varied by a factor of ∼4.5 on the timescale of several years. Very generally, Maoz et al. (2005) found, that nuclear UV variability in LINER galaxies with radio cores is very common. (3) Meusinger et al. (2010) observed a high-amplitude (factor 20) UV flare from the quasar J004457+4123, which they interpreted as either a microlensing event or else a TDE. (4) Nikolajuk and Walter (2013) reported the discovery of a hard X-ray flare with *INTEGRAL*, associated with the Seyfert galaxy NGC 4845. Because of the high amplitude of variability, the authors strongly favored a tidal disruption scenario; in this case the disruption of a giant planet. (5) The galaxy XMM J061927.1-655311 was found in a high-amplitude flaring state (factor >140) with *XMM-Newton* (Saxton et al., 2014) at $L_{\rm x,peak} \sim 10^{44}$ erg/s. Optical follow-up spectroscopy revealed low-level AGN activity (even though the spectrum looks peculiar and narrow emission lines are very faint). The X-rays and UV, observed with *Swift*, declined subsequently. The event was interpreted as either a TDE or a change in accretion rate in a long-lived AGN.

8. Future TDE surveys

Upcoming sky surveys will find TDEs in the hundreds or thousands, including in the radio with SKA (Donnarumma et al., in press), in the optical with LSST (van Velzen et al., 2011a) and in hard X-rays with LOFT (Rossi et al., 2015). Further, a dedicated X-ray transient mission is under consideration in China, which has among its prime goals the detection and study of TDEs in large numbers; the soft X-ray mission *Einstein Probe* (Zhao et al., 2014; Yuan et al., in press). *Einstein Probe* is designed to carry out an all-sky transient survey at energies of 0.5–4 keV. The concept is based on a wide-field micro-pore Lobster-eye imager (60° × 60°), and a more sensitive narrow-field instrument for follow-ups. The large number of new events and the well-covered lightcurves will enable a wealth of new science. In particular, X-rays will be sensitive to relativistic effects and accretion physics near the last stable orbit.

Meanwhile, *Swift* will continue to greatly contribute to this field, including searching for the re-emergence of bright X-rays from Swift J1644+57 itself, predicted by some models.

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[2] At the same time, a TDE in a gas rich environment like a starburst galaxy will inevitably excite emission lines which temporarily look like an AGN (e.g., Komossa et al., 2008). Therefore, repeat optical spectroscopy after a luminous flare is required, in order to assess whether any narrow lines are persistent or vary and ultimately fade.

[3] We note in passing, that IC 3599 is not a classical NLS1 galaxy, though, since it lacks the strong, characteristic FeII emission, typical for these galaxies, and since the only available optical high-state spectrum (Brandt et al., 1995) was just a snapshot of the fading broad emission lines responding to the flare, and the full line width can therefore be much higher than the value of 2000 km/s typically used to define NLS1 galaxies as a class.

[4] For example, 1E1615+061 (factor 100, Piro et al., 1988), WPVS 007 (factor 400, Grupe et al., 1995b; Vaughan et al., 2004; Grupe et al., 2013), PHL 1092 (factor 200, Miniutti et al., 2009), GSN 069 (factor 240, Miniutti et al., 2013), and RXJ2317-4422 (factor 60, Grupe et al., in press).

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