Tidal disruption of stars by supermassive black holes – XMM-Newton highlights and the next decade

S. Komossa\textsuperscript{1,2,*}

\textsuperscript{1} National Astronomical Observatories, Chinese Academy of Sciences, Beijing, China
\textsuperscript{2} QianNan Normal University for Nationalities, Longshan Street, Duyun City of Guizhou Province, China

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This article provides a summary of XMM-Newton highlights on stellar tidal disruption events. First found with ROSAT, ongoing and upcoming sky surveys will detect these events in the 1000s. In X-rays, tidal disruption events (TDEs) provide us with powerful new probes of accretion physics under extreme conditions and on short timescales and of relativistic effects near the SMBH, of the formation and evolution of disk winds near or above the Eddington limit, and of the processes of high-energy emission from newly launched radio jets. TDEs serve as signposts of the presence of dormant, single black holes at the cores of galaxies, and of binary black holes as well, since TDE lightcurves are characteristically different in the latter case. XMM-Newton has started to contribute to all of these topics, and a rich discovery space is opening up in the next decade.

1 Introduction

Supermassive black holes (SMBHs) can violently disrupt stars in their vicinity. The subsequent accretion of stellar material produces spectacular flares in the X-ray sky, and therefore can reveal the actual presence of the SMBH, even and especially if the black hole itself is usually dormant and does not harbour a long-lived accretion disk. Flares from tidally disrupted stars therefore represent independent signposts of the presence of SMBHs in non-active galaxies (e.g., Rees 1988) which are otherwise hard to detect, and provide us with a new route of estimating masses and spins of SMBHs. Because single stars are disrupted in the \textit{immediate} vicinity of a SMBH, this method of black hole detection is very complementary to another well-established detection method, which makes use of the motions of large ensembles of stars and gas at much larger distances from the SMBH.

Theoretical foundations of the stellar disruption process were laid in the 1970s, followed by early suggestions, how and where TDEs could play a role in astrophysical environments, including speculations about their contribution to fuelling active galactic nuclei (AGN), growing black holes, and powering gamma-ray bursts.

A star approaching a SMBH will feel increasingly strong tidal forces. Once the self-gravity of the star can no longer withstand those forces, the star is ripped apart (Hills 1975). This happens at the tidal radius,

\[ r_t \simeq 7 \times 10^{12} \left( \frac{M_{\text{BH}}}{10^6 M_{\odot}} \right)^{1/2} \left( \frac{M_*}{M_{\odot}} \right)^{1/2} \frac{r_*}{r_\odot} \text{ cm} . \]  

Only a fraction of the stellar material will eventually be accreted, while the remainder is unbound and escapes the system. The bound stellar material follows Keplerian orbits of high eccentricity and returns to pericenter at a rate

\[ \frac{dM}{dt} \propto t^{-5/3} . \]  

Major observational signatures of TDEs, which aid their identification, include (1) a flare of electromagnetic radiation at high peak luminosity, (2) from the core of an otherwise quiescent, inactive galaxy, (3) with a lightcurve which characteristically shows a rapid rise followed by a decline on the timescale of months to years. (4) If the stellar material is accreted as quickly as it returns to the SMBH after it was initially spread over a range of Keplerian orbits, the X-ray lightcurve is expected to decline as \( t^{-5/3} \).

First events were identified in the 1990s (e.g., Komossa & Bade 1999) in the course of the soft X-ray all-sky survey carried out with the ROSAT satellite, in form of luminous, very soft, giant-amplitude X-ray flares from otherwise quiescent galaxies, matching well all order-of-magnitude predictions of tidal disruption theory (Rees 1988), including an overall lightcurve decline consistent with a \( t^{-5/3} \) law.

More recently, events have been found at other wavebands (review by Komossa 2015); in the UV, optical, and at hard X-rays, and with follow-up detections in the NIR and radio bands. Some of these come with transient optical emission lines from hydrogen, helium and iron coronal transitions. About 40 events have been identified by now.

From a theoretical point of view, the simulation of the tidal disruption and accretion of a star, including predictions of the detailed observational characteristics at any given time of the evolution (multi-waveband spectra and lightcurves)
poses many challenges (review by Lodato et al. 2015). Substan-
tial progress in recent years has addressed 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
 in different orbits, and for single stars as well as binary stars,
 and for spinning and non-spinning black holes (e.g., Bon-
 nerot et al. 2016, Chen et al. 2016, Coughlin et al. 2016a,
 Coughlin et al. 2016b, Franchini et al. 2016, Hayasuki et al.
 2016, Liu et al. 2016, Lu et al. 2016, MacLeod et al. 2016,
 Mainetti et al. 2016a, Metzger & Stone 2016, Ricarte et al.
 2016, Roth et al. 2016, Sadowski et al. 2016, and references
 therein; review by Lodato et al. 2015).

X-ray observations of TDEs probe the inner parts of the
accretion disk, and are of outstanding importance for our
understanding of accretion physics under extreme condi-
tions, and on very short timescales, including the evolution
of the accretion disk through several accretion regimes from
super- to very sub-Eddington on the timescale of only years.

2 Highlights from XMM-Newton

The X-ray mission XMM-Newton was launched in 1999
(Jansen et al. 2001). The satellite is equipped with CCD ar-
rays, sensitive between (0.2-12) keV, with moderate spectral
resolution, and a spatial resolution of 6” (Turner et al. 2001,
Strüder et al. 2001). High-resolution spectral information
is provided by the Reflection Grating Spectrometer, RGS
(den Herder et al. 2001). Additional optical/UV informa-
tion is delivered by an onboard small optical/UV telescope,
the Optical Monitor (OM; Mason et al. 2001).

In addition to pointed observations, XMM-Newton car-
rries out a slew survey, which registers X-ray photons along
the path while moving from one target to another one,
performing a mini-survey of the sky that way. Further, a
mode of Target of Opportunity (ToO) observations allows for
rapid follow-ups of flaring and transient sources, with a
response time on the order of days.

This section provides an overview of TDE results ob-
tained with XMM-Newton, including the discovery of new
events, and follow-ups of remarkable events first identified
at other wavebands. These observations have added substan-
tially to our understanding of the early evolution of TDEs,
and the underlying accretion and jet physics.

2.1 First hard X-ray follow-up of a TDE: spectral
hardening of RXJ1242–1119

The TDE RXJ1242–1119 was first identified by its lumi-
nous X-ray flare ($L_{\text{x,peak}} > 10^{44}$ erg/s) detected with the
ROSAT X-ray observatory (Komossa & Greiner 1999). It is
located in an inactive host galaxy at redshift $z = 0.05$. It was
the first TDE to be followed-up at hard X-rays with Chan-
dra and XMM-Newton, and the first, for which an XMM-
Newton (CCD) spectrum could be obtained (Komossa et al.
2004). While its initial ROSAT X-ray spectrum was excep-
tionally soft ($\Gamma_{X} \approx -5$, or $kT_{bb} = 0.06$ keV), it had hard-
ened significantly ($\Gamma_{X} = -2.5$) when observed with XMM-
Newton (Komossa et al. 2004, Halpern et al. 2004), per-
haps implying the formation of a disk corona, which was not
present in the very early stages of TDE evolution, and/or a
change in accretion mode. A similar hardening of the X-ray
spectrum was observed on shorter timescales for NGC 5905
(Komossa & Bade 1999) and more recently in other TDE
candidates (e.g., Nikolajuk & Walter 2013). These follow-
up observations also revealed a very high amplitude of X-
ray decline of RXJ1242-1119, exceeding a factor of 1500
on the timescale of a decade, implying a strong change in
the accretion conditions on relatively short timescales. Such
a high amplitude of variability has not been observed in any
AGN.

At high-state, the accretion rate of RXJ1242–1119 was
below the Eddington limit, given its black hole mass of
$M_{\text{BH}} \approx 10^8 M_\odot$, estimated from the XMM-Newton Opti-
tical Monitor (OM) blue magnitude, and applying SMBH –
host scaling relations (Komossa et al. 2004). Based on the
observed lightcurve, the integral $\int L(t) dt$ provides us with
a lower limit on the total emitted energy of the event, $E > 1.6 \times 10^{51}$ ergs. This implies a lower limit on the amount
of stellar material which was accreted, $M_x > 0.01 \eta_{0.1} M_\odot$,
where $\eta = 0.1 \eta_{0.1}$ is the efficiency.

2.2 Discovery of new soft X-ray TDEs based on
the XMM-Newton slew survey: early-phase lightcurves

A dedicated search for new TDEs near maximum, including
(rapid) multi-wavelength follow-ups, is being carried out
based on the XMM-Newton slew survey (Esquej et al. 2007,
2008, Saxton et al. 2012, 2015, 2017). Events near high-
state are identified by cross-correlation with the ROSAT
database, and TDE candidates with soft spectra and high
amplitudes of variability are selected for follow-ups, includ-
ing optical spectroscopy in order to confirm non-active host
galaxies.

Among these events, SDSSJ121036.02+300305.5 has
the best-covered first-year X-ray lightcurve. It was detected
in an XMM-Newton slew in 2010 with a flux 56 times
higher than an upper limit from ROSAT, with a high peak
luminosity of $L_x = 3 \times 10^{44}$ erg/s (Saxton et al. 2012).
Its X-ray lightcurve shows an overall decline by a factor
$\sim 300$ over 300 days, superposed onto which is strong vari-
ability, reaching up to a factor of $>50$, when the source
is no longer detected by Swift. The host galaxy, at redshift
$z = 0.146$, is inactive, and no broad Balmer lines or coro-
nal lines have been detected in response to the X-ray flare,
in spectra taken 12 days and 11 months after discovery.

Unlike other TDEs, SDSSJ121036.02+300305.5 does not
show an X-ray spectral hardening with time, but remains
relatively soft, and its XMM-Newton X-ray spectrum is not
well fit by black-body-like thermal emission, neither by a
single powerlaw. Instead, the spectral shape is modelled
well by either a broken powerlaw, or Bremsstrahlung emission of $kT = 390$ eV. No radio emission was detected from SDSSJ120136.02+300305.5 by the VLA between 1.4 and 8.3 GHz, implying that no powerful radio jet was launched during this event.

The candidate TDE from NGC 3599, again identified during an XMM-Newton slew (Esquej et al. 2007, Esquej et al. 2008), is interesting because of its relatively long-lived X-ray emission, implying either a long-lived TDE, or else a permanent low-luminosity AGN in this LINER galaxy (Saxton et al. 2015). X-ray emission from NGC 5905 was bright and at similar levels during this event.

SDSSJ120136.02+300305.5 by the VLA between 1.4 and 5.0 GHz. No radio emission was detected from the inner region at the sound speed, causing an increase of the stability in the accretion disk, which propagates through the accretion disk, causing temporary interruptions of the accretion flow. The secondary black hole will perturb the stream of stellar material, causing temporary interruptions of the accretion flow on the primary, leading to epochs of characteristic deep dips and recoveries in the decline lightcurve (Liu et al. 2009, Ricarte et al. 2016). This signature has been observed in the lightcurve of SDSSJ120136.02+300305.5. While its X-ray lightcurve is consistent with thermal disk emission of temperature 0.17 keV and a rest-frame (0.24-11.8 keV) luminosity of $5 \times 10^{43}$ erg/s, subject to a high-velocity warm absorber (Lin et al. 2015).

2.4 A candidate sub-milli-parsec binary SMBH identified from a TDE lightcurve

If a TDE occurs in a binary supermassive black hole system, the binary will imprint its presence on the TDE lightcurve. The secondary black hole will perturb the stream of stellar material, causing temporary interruptions of the accretion flow on the primary, leading to epochs of characteristic deep dips and recoveries in the decline lightcurve (Liu et al. 2009, Ricarte et al. 2016). This signature has been observed in the lightcurve of the TDE from SDSSJ120136.02+300305.5. While its X-ray lightcurve is consistent with an overall decline, about a month after high-state, the X-rays fade by a factor >50 within a week, and remain undetected between day 27 and day 48 after discovery. Then, the X-rays bright again, followed by a second disappearance. No excess absorption was detected in X-rays, and no jet was seen in radio follow-ups. Detailed simulations have shown that the lightcurve of SDSSJ120136.02+300305.5 can be reproduced well with a model of a SMBH binary of mass ratio $q \approx 0.1$ at 0.6 milli pc separation (Liu et al. 2014).

Tightly-bound SMBH binaries like this one, which have already overcome the “final parsec problem”, are prime sources of gravitational wave radiation once the two black holes coalesce. For a binary SMBH system in SDSSJ120136.02+300305.5 with a primary mass of $M_{BH} = 10^7 M_\odot$ and mass ratio $q=0.08$, an orbital timescale of 150 d and with orbital eccentricity $e = 0.3$ (Liu et al. 2014), the lifetime due to emission of gravitational waves is $t_{GW} \approx 2 \times 10^6$ yr.

Future observations of TDE lightcurves provide us with a powerful new tool of searching for compact binary candidates from a TDE lightcurve.
SMBHs, well below spatial separations of parsecs, and in inactive galaxies which do not harbour long-lived AGN, and where binary SMBHs are especially difficult to detect by other means (e.g., Komossa & Zensus 2016).

2.5 Follow-ups of the first jetted TDE discovered by Swift

The event Swift J1644+57, discovered with Swift in 2011, differs from previous TDEs, in that it was detected at hard X-rays and was accompanied by strong (beamed) radio jet emission (e.g., Burrows et al. 2011, Bloom et al. 2011, Zauderer et al. 2011, Berger et al. 2012, Zauderer et al. 2013, Levan et al. 2011, Mangano et al. 2016, Yang et al. 2016). Swift J1644+57 was first detected as a bright X-ray source by the Swift Burst Alert Telescope (BAT) in March 2011. Its (isotropic) peak luminosity exceeded $10^{48}$ erg/s. Its X-ray lightcurve shows a general downward trend, on which very rapid, very high-amplitude variability is superposed, changing on timescales as fast as 100s. The host galaxy at redshift $z = 0.35$ does not show signs of permanent optical AGN activity. Low-ionization emission lines indicate star-formation activity. The event is accompanied by unresolved and variable radio emission. The observations have been interpreted as the rapid onset of a powerful jet following the tidal disruption of a star. The event has the best-covered X-ray lightcurve of any TDE to date, and has motivated a large number of follow-ups and theoretical studies (review by Komossa 2015), with an emphasis on the question of jet launching under TDE conditions, and the role of magnetic fields (e.g., Tchekhovskoy et al. 2014).

XMM-Newton has observed Swift J1644+57 multiple times during the first year after discovery (Reis et al. 2012, Castro-Tirado et al. 2013, Gonzales-Rodriguez et al. 2014). The first of these follow-ups was performed a few days after the BAT trigger. Evidence for a possible QPO at 5 milli Hz was reported by Reis et al. (2012). The QPO is only present in hard X-rays (2-10 keV) and only in one of the XMM-Newton observations (the one taken $\sim 19$ d after the BAT trigger), as well as in Suzaku data. Reis et al. suggested an origin in the inner accretion disk (see also Abramowicz & Liu 2012), while an association with turbulence in the accretion flow or resonances in the relativistic jet could not be ruled out.

Recently, Kara et al. (2016) reported the detection of a reverberation signal in X-rays, arising when gravitationally redshifted photons from the iron Kα emission line reflect off the inner accretion disk. These observations indicate, that the bulk of the X-ray emission at early times is dominated by the accretion disk. From the reverberation time lag, a SMBH mass of a few $10^6 M_\odot$ was estimated, confirming a highly super-Eddington accretion flow.

Swift continued to monitor Swift J1644+57 at daily to weekly time intervals, to follow the lightcurve decline. After $\sim 1.5$ yr, the X-rays from Swift J1644+57 suddenly dropped by a factor $\sim 100$, and have remained faint ever since (at $L_x = 5 \times 10^{42}$ erg/s, with $\Gamma_x \sim 1.9$), no longer detected by Swift, but only in deeper observations of Chandra and XMM-Newton (Zauderer et al. 2013, Mangano et al. 2016, Levan et al. 2016). The reason for this dramatic change is not yet fully understood. The low-state X-rays may arise from the forward shock associated with the radio jet (Zauderer et al. 2013), but have not yet faded further so far, while the radio emission does (Yang et al. 2016). Cheng et al. (2016) explored the possibility that the low-state X-ray emission arises from Thomson scattering of the primary X-rays off surrounding plasma. A persistent low-luminosity AGN is an unlikely explanation for the long-lived low-state X-rays, since the X-ray luminosity is still significantly higher than expected from the faint, low-mass host galaxy (Levan et al. 2016). The low-state X-ray spectrum is rather hard, inconsistent with thermal emission from the accretion disk (Zauderer et al. 2013), but possibly due to Comptonized emission from a disk corona (Mangano et al. 2016).

This and future observations of jetted TDEs provide us with a completely new probe of the early phases of jet formation and evolution, and the jet-disk connection, in an otherwise quiescent environment without past X-ray and radio-AGN activity.

2.6 Detection of absorption lines in a TDE X-ray spectrum

The first X-ray grating spectrum of a TDE was presented recently (Miller et al. 2015). ASASSN14li at redshift $z = 0.02$ was first identified based on its optical variability in a supernova search survey (Jose et al. 2014, Holoien et al. 2016). It is accompanied by luminous X-ray, and faint, variable radio emission (van Velzen et al. 2016, Alexander et al. 2016).

The high-resolution RGS X-ray spectrum of ASASSN14li revealed the presence of several narrow absorption lines, superposed on soft, thermal continuum emission ($kT = 0.05$ keV). Velocity shifts of few 100 km/s imply matter in outflow. The material is highly ionized with an ionization parameter on the order of $\log \zeta \simeq 4$, and a column density of the ionized gas of order few $10^{21} \text{ cm}^{-2}$.

Narrow-line variability (mostly in the outflow velocity) was used to argue for a location of the outflowing material close to the SMBH. Miller et al. (2015) suggest a rotating wind from the inner, super-Eddington, nascent accretion disk, or a filament of the disrupted star itself, as most likely origin of the absorbing gas.

This observation has opened up a new window into studying accretion-driven winds powered by TDEs in X-rays. Future absorption line spectroscopy will tightly constrain the physical properties, abundances, and velocity fields of newly launched disk winds, and the stellar material itself.
3 Future opportunities and the next decade with XMM-Newton

Chances of discovering new TDEs with XMM-Newton arise from the continuing dedicated search for transients in the XMM-Newton slew survey, in the XMM-Newton archive, in clusters of galaxies, and from serendipitous detections. Chances for deep spectroscopic follow-ups of TDEs with XMM-Newton will additionally open up, when new TDEs are identified in ongoing or upcoming sky surveys. These include current surveys such as those carried out with PTF, Pan-STARRS, and ASAS-SN in the optical, or Swift and MAXI in X-rays and γ-rays, as well as future surveys like with LSST and with SKA. In X-rays, several proposed missions like the Chinese Einstein Probe will carry out dedicated transient searches, and are likely to have an overlap in time with XMM-Newton.

In the future, the performance of XMM-Newton might be further enhanced by aiming at an even more rapid response after the discovery of new TDEs, by increasing the frequency and depth of (rapid) follow-up X-ray observations if interesting spectral features in emission or absorption are present, by setting up dedicated large programs and/or automated follow-ups of transients or TDEs in particular, and by increasing the mutual agreements with other observatories for joint multi-wavelength follow-ups, for instance in the radio regime with the VLA, EVN or FAST.

In summary, deep X-ray observations with XMM-Newton provide us with a unique chance of probing accretion physics down to the last stable orbit and under extreme conditions (near-Eddington up to hyper-Eddington accretion rates). They allow us to follow the evolution of disk winds and coronae, search for relativistic (precession) effects in the Kerr metric, perform iron-line reverberation mapping, estimate BH spin, carry out absorption/emission-line spectroscopy of ionized matter in outflow (either stellar debris or accretion disk winds), and study the jet-disk coupling and jet evolution in jetted events. All of these are now within reach and first examples of these processes have been found with XMM-Newton recently, opening up a rich discovery space in the next decade.

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