Jetted and non-jetted stellar tidal disruption events (TDEs)

S. Komossa, MPIfR Bonn

Tidal capture & disruption of stars by SMBHs

“The best diagnostic for a BH’s presence would be some inevitable concomitant that cannot be explained in any other way.”

tidal disruption of stars by SMBHs

- disruption at $r = r_{\text{tidal}}$, with tidal radius $r_{\text{tidal}} = R_*(M_{\text{BH}}/m_*)^{1/3} = 7 \times 10^{12} M_{\text{BH},6}^{1/3} (R_*/R_{\text{sun}}) (m_*/m_{\text{sun}})^{-1/3}$ cm
  - solar-type stars swallowed whole above $M_{\text{BH}} \sim 10^8 M_{\text{sun}}$
  - disruption of WDs requires $M_{\text{BH}} < 10^5 M_{\text{sun}}$

- high initial gas supply rate, up to highly super-Eddington $\rightarrow$ high $L_{\text{peak}}$

- bbdy temperature at $r_t$ $T \sim 10^{5-6}$ K

- $\sim 90\%$ of the stellar material is unbound

- event rate $10^{-4-5}$ yr/galaxy

- return rate $\frac{dm}{dt} \sim t^{-5/3}$
tidal disruption of stars by SMBHs

- detection of IMBHs, $< 10^6 \, M_{\odot}$

- new probe of accretion physics down to last stable orbit, from highly super-Eddington to sub-Eddington within yrs; & of BH spin and jet formation

[Graham+11]
Luminous TDEs in soft X-rays – first detections (ROSAT)

- $L_{x, \text{peak}}$ up to several $10^{44}$ erg/s
- Very soft X-ray spectra near peak ($kT_{BB} \sim 0.04$-0.1 keV); then hardening within yrs
- Decline consistent with predicted $t^{-5/3}$ law, plus drop at $t >$ several yrs
- Amplitudes of decline up to factor 1000-6000

[Bade+96, Komossa & Bade 99, Komossa & Greiner 99, Greiner+ 00, Halpern+ 04, Komossa+ 04]

Figure 3. ROSAT high-state lightcurve of NGC 5905, observed during the RASS. It shows a rise within several days toward the observed peak of $L_{x, \text{peak}} = 7 \times 10^{42}$ erg/s.
luminous TDEs in soft X-rays – first detections (ROSAT)

- $L_{x,\text{peak}}$ up to sev. $10^{44}$ erg/s
- very soft X-ray spectra near peak ($kT_{\text{BB}} \sim 0.04$-0.1 keV); then hardening within yrs
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- host galaxies are optically inactive

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- host galaxies are optically inactive

- $M_{BH} \sim 10^6$-$8$ $M_{\text{sun}}$
- $m^*,\text{acc} < 10\%$ $M_{\text{sun}}$

[Bade+96, Komossa & Bade 99, Komossa & Greiner 99, Greiner+ 00, Li+ 02, Halpern+ 04, Komossa+ 04]
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plus 1-- few in classical AGN [e.g., Nikolajuk & Walter+ 13]

[review: Komossa 15]
X-ray TDEs: dedicated searches for new events (XMM & Chandra)

~ 10 events identified; overall properties very similar to previous (ROSAT) soft X-ray TDEs:
- extreme X-ray softness near max
- high peak luminosities, up to few $10^{44}$ erg/s
- decline by typ. factors $\sim > 100$
  (ROSAT: > 1000-6000)
- (optically) quiescent galaxies

→ important probes of accretion physics in early stages of TDE evolution;
  including the super-Eddington phase

rate estimates: $10^{-4} - 5$ /yr/gal
(based on: RASS, XMM-slew, Chandra DF, gal. clusters)

[Donley+ 02, Esquej+ 08, Luo+ 08, Maksym+ 10, Khabibullin+14]

[Esquej+ 07,08, Cappelluti+ 09, Maksym+ 10,13, Lin+ 11,15, 16—prep., Saxton+ 12, 14,16—prep., Donato+ 14, review: Komossa 15]
TDEs with XMM & Chandra

SDSSJ1201+30 (z=0.146)

$L_{x,hi} = 3 \times 10^{44}$ erg/s
overall decline, + high-ampl. var
complex X-ray spectrum

- no emission lines; neither host nor TDE
- no VLA radio detection:
  $f < 0.1$ mJy (at 8 GHz) after ~1yr
- $M_{BH} \sim 10^6$-$7$ $M_{\odot}$

[Saxton+ 12, Liu, Li, Komossa 14]
TDEs with XMM & Chandra

2MASSJ07-85 \( (z=0.017) \)

\[
L_{x,hi} = \text{few } 10^{43} \text{ erg/s}
\]

fast variability (XMM): doubling timescale 400s
soft spectrum with hard tail

no optical emission lines \( \rightarrow \) inactive galaxy

[16--in prep ]
3XMMJ1521+0749

$L_x = 5 \times 10^{43}$ erg/s

ultra-soft spectrum, $kT \sim 0.1$ keV, subject to fast-moving warm absorber ($v \sim 0.1$ c)

not detected in X in any follow-ups; amplitude of variability: factor 260

X-emi coincident with centre of inactive galaxy at $z=0.18$

BH mass: $M_{\text{BH}} = \text{few } 10^7 M_{\odot}$

[Lin+ 15]
first high-resolution X-ray spectroscopy of a TDE

- optically identified TDE (z=0.02) **ASASSN14li**, with luminous X-rays

- declining radio emission indicates presence of low-power jet/outflow (+ permanent component indicating permanent low-level AGN)

- XMM-RGS: thermal conti (kT ~ 0.05 keV) & highly ionized matter near BH in outflow
  \[ v = \text{few 100 km/s} \]

→ new probe of early formation & evolution of disk wind and/or stellar debris

[Jose+ 14 Atel #6777, Miller+ 15]
TDEs in gas-rich environments: emission lines

- super-strong Fe coronal lines & HeII
- $L_{[\text{Fe}X],\text{hi}} = 4 \times 10^{40}$ erg/s
- fade by factor 10, in ~3yrs

- unusual Balmer profile; incl. redshifted broad comp., fading

- luminous MIR (Spitzer, 10-20 m), ~$10^{43}$ erg/s

- but faint X-rays, ~$10^{41}$ erg/s, few yrs after 'SDSS' high-state

- no clear signs of permanent AGN (from line ratios, absence of radio, opt pl, IRAS colours)

- $M_{\text{BH}} = 7 \times 10^6 \, M_{\odot}$ (from $\sigma_*$)

[Komossa+ 08, 09]
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[Komossa+ 08, 09]
TDEs in gas-rich environments: emission lines

very narrow double-peaked “horns” in Balmer lines:

→ lines excited by TDE, illuminating surrounding ISM (narrow lines), and stellar material (broad lines)? → new method of mapping phys. conditions in galaxy cores

[Komossa+ 08, 09]
TDEs in gas-rich environments: emission lines

several more TDE candidates with transient emission-lines from SDSS, PanSTARS, PTF, ASAS-SN; including in early stages, with strong Balmer lines

→ emission from the tidal debris which formed the temporary accretion disk
→ ongoing discussions:
  - do TDE candidates with absent H lines require He-rich stellar core, or photoionization-effects in solar gas?
  - why do their decline lightcurves imply ~constant $T$, $\sim 10^4$ K?
  - why do most opt-UV TDE candidates lack X-ray emission?

[e.g., Komossa+ 09, Wang+ 11, 12, van Velzen+ 11, Gezari+ 12, Guillochon+ 14, Gaskell+ 14, Holoien+ 14, 16, Arcavi+ 14, ....]
A Possible Relativistic Jetted Outburst from a Massive Black Hole Fed by a Tidally Disrupted Star

Joshua S. Bloom, 1,4 Dimitrios Giannios, 2 Brian D. Metzger, 2 S. Bradley Cenko, 2 Daniel A. Perley, 3 Nathaniel R. Butler, 2 Nial R. Tanvir, 2 Andrew J. Levan, 2 Paul T. O’Brien, 2 Linda E. Struble, 1,3 Fabio De Colle, 2 Enrico Ramirez-Ruiz, 2 William H. Lee, 2 Sergei Nakayshin, 3 Eliot Quataert, 5 Andrew R. King, 2 Antonino Cucchiara, 7 James Guilluchon, 6 Geoffrey C. Bower, 9,3 Andrew S. Fruchter, 10 Adam N. Morgan, 10 Alexander J. van der Horst 11

Gas accretion onto some massive black holes (MBHs) at the centers of galaxies actively powers luminous emission, but most MBHs are considered dormant. Occasionally, a star passing too near an MBH is torn apart by gravitational forces, leading to a bright tidal disruption flare (TDF). Although the black hole transient Sa 1644+ 78 initially displayed signs of the theoretically predicted properties of such an event, the follow-up monitoring of its optical and X-ray emission was limited.

An Extremely Luminous Panchromatic Outburst from the Nucleus of a Distant Galaxy


Variable x-ray and γ-ray emission is characteristic of the most extreme physical processes in the universe. We present multiband observations of a unique γ-ray-selected transient detected by the Swift satellite, accompanied by bright emission across the electromagnetic spectrum, and whose properties are unlike any previously observed source. We pinpoint the event to the center of a small, star-forming galaxy at redshift \( z = 0.3534 \). Its high-energy emission has lasted much longer than any γ-ray burst, whereas its peak luminosity was \( \sim 100 \) times higher than bright active galactic nuclei. The association of the outburst with the center of its host galaxy suggests that this phenomenon has its origin in a rare mechanism involving the massive black hole in the nucleus of that galaxy.

LETTER

Relativistic jet activity from the tidal disruption of a star by a massive black hole


Superimposed black holes have powerful gravitational fields with strong gradients that can destroy stars that get too close, producing a bright flare in ultraviolet and X-ray spectral regions from stellar debris that forms an accretion disk around the black hole\(^ {10} \). The source of the burst may have been some time between the two decades in the form of a small, isolated, slowly fading injection of emission from distant galaxies\(^ {11} \), but the burst of the stellar disruption event has not yet been observed. Here we report observations of a bright X-ray flare from the extragalactic transient Swift J164449.3+573451. This source increased in brightness in the X-ray band by a factor of at least 10,000 since 1990 and by a factor of at least 100 since early 2010. We conclude that we have captured the onset of relativistic jet activity from a supermassive black hole. A comparison paper\(^ {12} \) comes to similar conclusions on

LETTER

Birth of a relativistic outflow in the unusual γ-ray transient Swift J164449.3+573451


Active galactic nuclei, which are powered by long-term accretion onto central supermassive black holes, produce relativistic jets with lifetimes of at least one million years, and the observation of the birth of such a jet is therefore unlikely. Transient accretion onto a supermassive black hole, for example through the tidal disruption\(^ {11} \) of a star, thus offers a rare opportunity to study the birth of a relativistic jet. On 25 March 2011, an unusual transient source (Swift J164449.3+573451) was found\(^ 1 \), potentially representing\(^ 2 \) such an accretion event. Here we report observations spanning centurial to millimetric wavelengths and covering the first month of evolution of a luminous radio transient associated with Swift J164449.3+573451. The radio transient coincides\(^ 3 \) with the nucleus of an inactive galaxy. We conclude that we are seeing a newly formed relativistic outflow, launched by transient accretion onto a million-solar-mass black hole. A relativistic outflow is not predicted in this situation, but we show that the tidal disruption of a star naturally explains the observed high-energy properties and radio luminosity and the inferred rate of such events. The weaker beaming in the radio-frequency spectrum relative to γ-rays or X-rays suggests that radio searches may uncover similar events out to redshifts of \( z \approx 6 \).

On the discovery of Swift J164449.3+573451 by NASA’s Swift satellite, and the identification of a galaxy at a redshift\(^ {4} \) of \( z = 0.354 \) within Swift’s X-ray localization region (radius\(^ {4} \)), the 1.4 GHz radio observations of the transient on 20 March 2011 9.7 GHz with the Expanded Very Large Array (EVLA) at a frequency of 5.8 GHz and discovered an unresolved source with a flux density of 3.0 ± 0.7 Jy. Arometric monitoring suggested that the radio source coincided with the galaxy nucleus (Fig. 3), and was subsequently confirmed with other data. A follow-up EVLA observation of 0.9 Jy revealed that the
jetted TDEs: SwiftJ1644+57

• J1644+57 discovered with Swift BAT March 2011; no detection before March 25

• lightcurve overally declining
• plus rapid variability, $\Delta t \sim 100s$

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- \[ L_{x,\text{isotropic}} = 10^{45} -- 4 \times 10^{48} \text{ erg/s} \]
- lightcurve overally declining
- plus rapid variability, \( \Delta t \sim 100s \)
- \[ z_{\text{host}} = 0.35, \text{ optically inactive} \]
- no UV, opt var (exti), but NIR

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- $z_{\text{host}} = 0.35$, optically inactive
- *unresolved, variable, beamed radio emission*  

[Bloom+ 11, Burrows+ 11, Levan+ 11, Zauderer+ 11, multi-\text{λ} follow-ups: Aliu+11, Berger+ 12, Wirsema+ 12, Saxton+ 12, Reis+ 12, Aleksic 13, Zauderer+ 13, Castro-Tirado+ 13 & Gonzales-Rodriguez+ 13, Levan+ 16, Mangano+ 14, 16, Kara+ 16, Yang+ 16]
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→ rapid onset of a powerful jet, following tidal disruption

[Bloom+ 11, Burrows+ 11, Levan+ 11, Zauderer+ 11, multi-$\lambda$ follow-ups: Aliu+11, Berger+ 12, Wirsema+ 12, Saxton+ 12, Reis+ 12, Aleksic 13, Zauderer+ 13, Castro-Tirado+ 13 & Gonzales-Rodriguez+ 13, Levan+ 16, Mangano+ 14, 16, Kara+ 16, Yang+ 16]
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$\rightarrow$ rapid onset of a powerful jet, following tidal disruption

- sudden drop in X-rays after $\sim 1.5$ yr
- not seen in radio

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- unresolved, variable, beamed radio emission

- rapid onset of a powerful jet, following tidal disruption

- late-time X-rays remain faint, $\sim$constant, at $L_{x,\text{low}} = 5 \times 10^{42}$ erg/s

[Bloom+ 11, Burrows+ 11, Levan+ 11, Zauderer+ 11, multi-\lambda follow-ups: Aliu+11, Berger+ 12, Wirsema+ 12, Saxton+ 12, Reis+ 12, Aleksic 13, Zauderer+ 13, Castro-Tirado+ 13 & Gonzales-Rodriguez+ 13, Levan+ 16, Mangano+ 14, 16, Kara+ 16, Yang+ 16]
jetted TDEs: two more candidates with Swift:

**SwiftJ2058+0516**  
**SwiftJ1112-8238**

- $L_{x,\text{iso}} > 10^{47}$ erg/s
- $z_{\text{likely-host}} = 0.89$ (?) 

- $L_{x,\text{iso}} = 3 \times 10^{47}$ erg/s
- rapid variability, $\Delta t \sim 1000$s
- $z_{\text{likely-host}} = 1.19$, optically inactive
- $M_{\text{BH}} \approx \text{approx } 10^{7-8} M_{\odot}$
- luminous radio emi, likely beamed

→ many similarities with J1644

[Cenko+ 12, Brown+15, Pasham+15]
SwiftJ1644 follow-ups: modelling, theory, implications

- X-ray & radio emission mechanisms:
  do X-rays come from disc, inner jet, shocks from jet-ISM interaction, beamed component, ... ?

A 200-s Quasi-Periodicity Following the Tidal Disruption of a Star by a Dormant Black Hole
R. C. Reis, J. M. Miller, M. T. Reynolds, K. Gültekin, D. Maltra, A. L. King, T. E. Strohmayer

A model for the multiwavelength radiation from tidal disruption Swift J1644+57
P. Kumar, R. Barniol Duran, Ž. Bošnjak and T. Piran

Jiuzhou Wang, Wei-Hua Lei, Ding-Xiong Wang, Yuan-Chuan Zou, Bing Zhang, He Gao, and Chang-Yin Huang

Tidal disruption and magnetic flux capture: powering a jet from a quiescent black hole
Luke Zoltan Kelley, Alexander Tchekhovskoy and Ramesh Narayan

JETS FROM TIDAL DISRUPTIONS OF STARS BY BLACK HOLES
Julian H. Krolik and Tsvi Piran

Observing Lense-Thirring Precession in Tidal Disruption Flares
Nicholas Stone and Abraham Loeb
jetted TDE SwiftJ1644+57: how much above Eddington?

- spatially resolving the radio jet
  - search for superluminal motion with EVN phase-referencing, at 5 GHz
  - spatial resolution: 12 micro-arcsec
  - no superluminal motion detected, $\beta_{\text{app}} < 0.3$ c
  - no spatial extent detected

[Yang+ 16]
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[Yang+ 16]

Sadowski & Narayan 15

talks by Alexander Sadowski & Ken Oshuga, this meeting
jetted TDE SwiftJ1644+57: how much above Eddington?

detection of X-ray reverberation

[Kara+ 16]
soft X-ray (non-jetted) TDEs: how much above Eddington?

observed (0.1-2.4 keV) X-ray luminosities
soft X-ray (non-jetted) TDEs: how much above Eddington?
future TDE search & applications

• statistics: flare rates, frequency of IMBHs
  when flares detected in 1000s in current & future sky surveys in
  opt – X-ray – radio band (e.g., LSST—opt, Einstein Probe –X, SKA--radio)

• rapid follow-ups:
  → in X-rays: - highest amplitudes (highest contrasts vs hosts, x $10^{4-6}$),
   - best chances for observing relativistic effects (broad lines, precession),
   - best probe of accretion physics down to last stable orbit, under extreme
     conditions, incl. super-Eddington phase
  → in optical(UV):
    esp. emi.-lines: - reverberation mapping of circum-nuclear gas,
    - of stellar debris, - TDE-EUV conti, - CL atomic parameters
  → in radio, hard X-rays: new probe of jet formation & evolution (but not
    in all events) in pristine environment; jet-disk coupling

• GWs (+em) from compact cores of partially stripped stars (WDs & NS)
• new discovery space: signposts of SMBBHs, and recoiling BHs, ...
  (→ repeat TDEs, off-center TDEs, no-host TDEs)