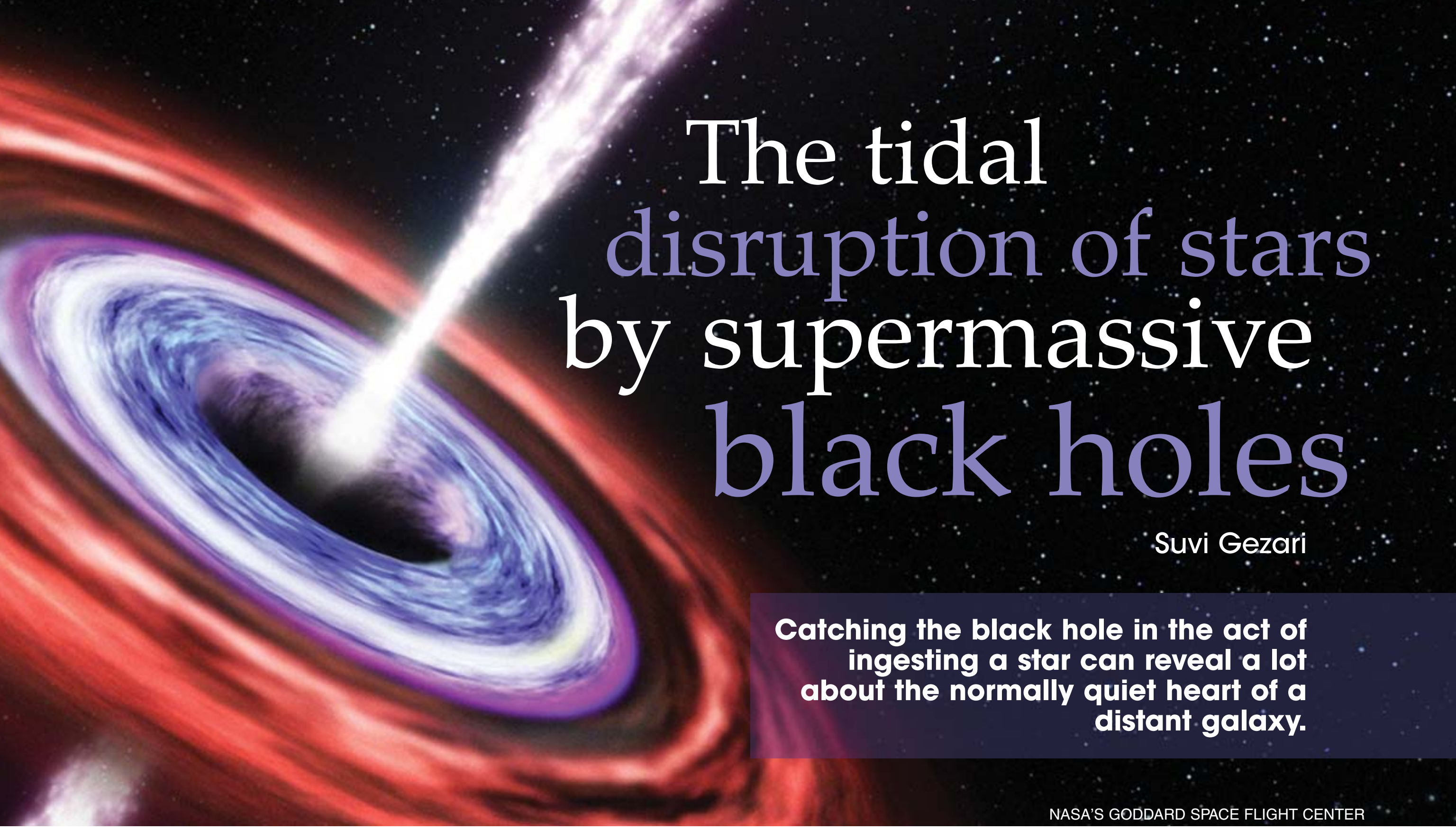

The tidal disruption of stars by supermassive black holes

Suvi Gezari

Catching the black hole in the act of ingesting a star can reveal a lot about the normally quiet heart of a distant galaxy.

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Supermassive black holes (SMBHs), a million to 10 billion times the mass $M_\odot$ of the Sun, lurk in the nuclei of almost all galaxies, including our own. Those colossal beasts provide a unique opportunity to probe gravity in its strong-field regime, where the curvature of spacetime is at its most extreme. Unfortunately, they're difficult to study directly. Nothing can escape the event horizon surrounding a black hole, not even light.

The only way to detect a black hole is either by its gravitational pull on nearby bodies and gas, or by light emitted from gas heated as it's funneled down to its doom. Most SMBHs are either too distant for telescopes to resolve the small central galactic region over which their gravity dominates the motions of stars and gas or too dim for lack of material to feed them. But when a star does wander close enough to an SMBH, the consequences are dramatic—and observable out to cosmological distances.

Snacking on stars

Theorists first proposed in the late 1970s that if a star passed close enough to an SMBH, tidal forces would rip the star apart, producing a stream of debris that would then be swallowed by the black hole. The luminous flare of radiation resulting from the gas heating up on its way down could, it was argued, serve as a signpost for an otherwise clandestine black hole.[1]

The distance at which an approaching star would be tidally disrupted by an SMBH of mass M_{BH} is called the black hole's tidal-disruption radius R_T. It's given roughly by

$$R_T \approx R_*(M_{BH}/M_*)^{1/3}, \qquad (1)$$

where M_* and R_* are the star's mass and radius.

Figure 1 is a schematic diagram of the trajectory of a star and its shredded debris in such a tidal-disruption event (TDE). At least half the gas liberated from the disrupted star escapes the SMBH's gravity in an expanding high-velocity tail that never returns to contribute to the TDE flare. The rest of the stellar debris remains gravitationally bound in a range of elliptical orbits that gradually deliver it to an accretion disk of stellar debris in the black hole's immediate vicinity. Over the duration of the TDE flare, the black hole feeds without hesitation from that transitory accretion disk, newly formed just outside its event horizon.

More fundamental than R_T is a black hole's Schwarzschild radius,

$$R_S = 2GM_{BH}/c^2, \qquad (2)$$

where G is Newton's gravitational constant and c is the speed of light. For a nonspinning black hole, R_S is the radius of its event horizon. For a typical star approaching a typical SMBH, R_S is much smaller than R_T. But it grows faster with M_{BH}. So there must be some very large M_{BH} at which R_S catches up with R_T, and doomed stars discreetly disappear from view before they're torn apart. (See figure 2.)

What would happen if the Sun approached the $4.3 \times 10^6\ M_\odot$ black hole at the center of the Milky Way? Nothing, at first—until the Sun got well within 1 astronomical unit of the black hole (1 AU is the mean Earth–Sun separation). So, given the very close approach required for a star to be torn apart by an SMBH, it's not surprising that such events are quite rare.

The rate at which stars are disrupted depends on

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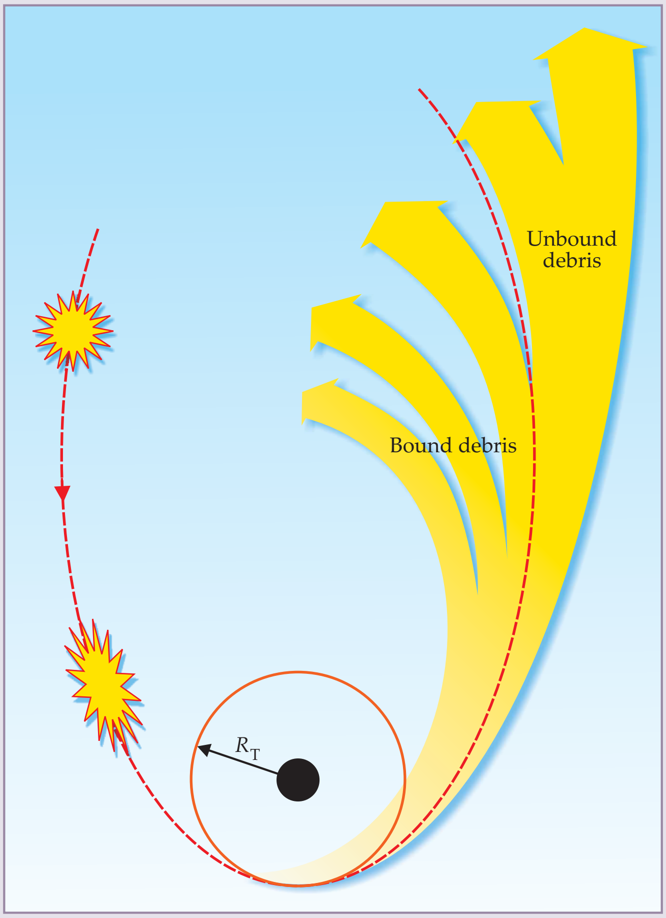


Figure 1. A star that comes within the tidal-disruption radius R_T of the supermassive black hole at the heart of a galaxy will be torn apart by the black hole's gravity. Roughly half of the gaseous stellar debris remains gravitationally bound in a range of highly eccentric elliptical orbits that typically bring it back over a course of months to years to be consumed by the black hole. Viscously heated as it's finally funneled down toward the black hole's event horizon (the black dot's edge), the gas radiates a telltale flare that fades as the feeding subsides. The rest of the debris escapes the black hole's gravity in an expanding high-velocity tail. (Adapted from ref. 1.)

the random gravitational scatterings of stars off each other in the central regions of galaxies. Dynamical models of stellar orbits in galaxy cores predict that only once in thousands of years, in any one galaxy, will a star be kicked into a fatal trajectory around the black hole. Therefore, only large surveys monitoring hundreds of thousands of galaxies are likely to catch any in the act of tidally disrupting a star.

The search for candidates

The first observational candidates for TDEs emerged from an all-sky survey in 1990–91 by the German soft-x-ray satellite *ROSAT*. A decade later, archival searches of that survey revealed luminous outbursts from several galaxies whose centers had previously exhibited no activity.[2] Those soft-x-ray outbursts were interpreted as TDEs in otherwise quiescent central SMBHs. The global rate of the TDEs deduced from the archival search was within the range of theoretical predictions.[3] Furthermore, the spectral shapes of the outbursts suggested that they were radiation from dense, million-degree gas heated by accretion near the event horizons of SMBHs.

An exciting application of TDEs is their use as beacons and probes of dormant SMBHs hidden in the centers of galaxies. Detailed observations of the events reveal properties not only of the disrupted star but also of the galaxy's central black hole. It's well known that the masses of SMBHs are tightly correlated with the masses and luminosities of their host galaxies. That correlation implies a direct connection between SMBH formation and the growth of galaxies through mergers and star formation. Probing the demographics of SMBHs should become a key step toward understanding the role of black holes in galactic evolution.

Flare peaking and decay

Numerical simulations of the stellar debris's orbital "fallback" onto the accretion disk from which the SMBH feeds have shown that the early evolution of the accretion rate is sensitive to the black hole's mass as well as the mass and internal structure of the star being disrupted.[4] In particular, the interval between the disruption time t_D and peak luminosity t_P of the TDE flare can be used to weigh the SMBH. In the approximation that the disrupted star had uniform density, one gets

$$\Delta t \equiv t_P - t_D \approx 41 \text{ days} \times \left(\frac{R_*}{R_\odot}\right)^{3/2} \left(\frac{M_{BH}}{10^6 M_\odot}\right)^{1/2} \left(\frac{M_\odot}{M_*}\right). \quad (3)$$

In practice, although TDE light curves (recorded brightness versus time) fix t_P with good precision, they can't adequately constrain the starting time t_D. But detailed numerical simulations for stars of different internal structures provide accretion-rate templates that can be fitted to light curves to determine t_D.

Most stars have nothing like uniform density. Lower density near the surface slows the rise to peak luminosity, relative to what equation 3 predicts, because there's less early debris with short orbital return times. Figure 3 shows model calculations of the rate at which a Sun-like star's debris falls back onto the black hole's accretion disk, as a function of time since t_D, for different SMBH masses.[5] The luminosity of the TDE flare is proportional to the fallback rate. The curves show the strong dependence of the rise time Δt on the SMBH mass. So the rise time can, in principle, serve as a black hole mass indicator. At late times, the debris returns with a characteristic $t^{-5/3}$ power-law decay, dictated by the range of Keplerian orbits of the gravitationally bound debris.

Figure 3 also indicates the so-called Eddington limits on the fallback rates for different SMBH masses. The calculated limits assume that accreting material emits radiation with a typical efficiency of about 10%. Above the Eddington limit, the outward radiation pressure wins out over gravity. If the stellar debris falls isotropically toward the black hole and the system is in hydrodynamic equilibrium, material arriving at rates above the Eddington limit should be blown away rather than accreted. But near t_P, the model calculations do predict accretion rates that exceed the Eddington limit for the lighter SMBHs.

Stellar diversity

Even with a good handle on Δt, the unknown stellar mass and radius in equation 3 leave a large window of uncertainty as to the black hole's mass. Furthermore, the radial density profile of the star is also unknown. In the long "main-sequence" stage of their lives, stars burn hydrogen into helium in their cores. But internal structures of main-sequence stars vary widely, depending on heat-transfer mechanisms that, in turn, depend on mass.

One might think that such internal-structure diversity produces yet another serious uncertainty in deducing M_{BH} from Δt. But it turns out that a correlation between the masses and radii of main-sequence stars largely cancels out the effect of mass-dependent internal structure on the rise time.[4] Thus observations of Δt can constrain the black hole's mass even when the mass of the disrupted main-sequence star is unknown.

Although main-sequence stars are the most common in a galaxy, there will still be a contribution of TDEs from stars that have evolved to later stages: red giants, white dwarfs, and even more exotic stellar populations found only in the vicinity of SMBHs. Fortunately, given the extreme radii of red giants and white dwarfs—of order 100 $R_\odot$ and 0.1 $R_\odot$—their TDE light curves have extreme time scales that are easily recognized.

We also expect to see the tidal disruption of giant gas clouds, albeit at much larger distances from the black hole due to their fragility. Indeed, the SMBH hole at the center of our galaxy was reported[6] in 2012 to be in the act of tidally shredding an Earth-mass dusty gas cloud at a distance of 100 AU. From that large distance, the time scale on which the gas is consumed by the black hole is quite long—hundreds of years. But observers are following the dynamical evolution of the tidally distorted gas cloud in real time, eagerly monitoring the galactic center at all wavelengths from radio to x rays in the hopes of detecting signatures of the SMBH's hydrodynamic interaction with the hot gas in its environment.

Multiwavelength coverage

Though the x-ray-flaring galaxies detected by *ROSAT* were the first strong evidence that the theoretically proposed TDEs really do occur in galactic nuclei, the lack of multiwavelength coverage and light-curve sampling made it difficult to constrain the parameters of those events—in particular the SMBH masses. In fact, observations of the early, rising phase of a TDE light curve, which is the most diagnostic phase for determining the SMBH and star properties, remained elusive until very recently.

As a postdoc at Caltech in 2006, I initiated searches for TDEs at UV and optical wavelengths in order to improve the temporal sampling of candidates.[7] Although those low photon energies are not ideal for probing the very hot accreting gas expected in a TDE, they constitute the wavelength range in

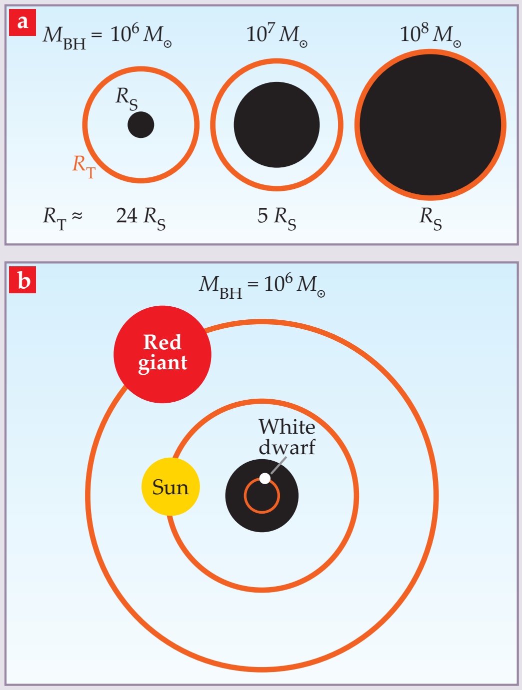


Figure 2. The tidal-disruption radius R_T depends on the mass M_{BH} of the black hole doing the disrupting and on the properties of the star being disrupted. (Nothing here is shown to scale.) **(a)** R_T (orange circles) grows like $(M_{BH})^{1/3}$. But the black hole's Schwarzschild radius R_S (black-disk boundaries) grows like M_{BH}. For the Sun-like star of this illustration, R_S and R_T become equal at $M_{BH} \approx 10^8\, M_\odot$. So the tidal disruption of a Sun-like star by a (nonspinning) black hole heavier than $10^8\, M_\odot$ couldn't be seen. **(b)** For a given black hole mass, R_T depends sensitively on stellar size. The stellar radii of red giants and white dwarfs are, respectively, a hundred times bigger and smaller than the Sun's. Near a $10^6\, M_\odot$ black hole like the one at the Milky Way's center, a white dwarf would irretrievably disappear behind the central black hole's R_S before being torn apart.

which the most advanced wide-field temporal surveys are being conducted. My coworkers and I have so far discovered a total of seven candidate TDEs in the UV and optical. Our prompt multiwavelength follow-up of those events—in particular with NASA's *Chandra* x-ray orbiter and ground-based optical spectrographs—has enabled us to constrain their total energy outputs and temperatures, and look for direct signatures of the stellar victims.

Our most promising TDE candidate, PS1-10jh, was discovered in 2010 by coordinated monitoring of a patch of sky every two or three days with NASA's *GALEX* UV telescope and the Pan-STARRS1 optical survey telescope in Hawaii.[8] We detected a flare from the nucleus of a normally inactive galaxy about 3 million light-years away. Our frequent sampling of the celestial patch let us catch PS1-10jh on its rise to peak luminosity (see figure 4).

The light curve, by itself, constrained the internal density profile of the star and yielded a black hole mass estimate blurred by uncertainties related to the mass and radius of the disrupted star. But we have extra information from spectroscopic observations of the event; they reveal broad emission lines from fast-moving ionized helium gas that fade along with the UV and optical flare.

Based on the chemical composition of the gas, we concluded that we were seeing the photoionized debris from the tidal disruption of a helium-rich stellar core. For the first time, we could constrain both the radial profile and the chemical composition of the star in a TDE. Helium stars, stripped of their hydrogen outer layers during the red-giant phase, had been predicted to exist in galactic cores. Models for such stripped red giants yielded a stellar mass and radius good enough to let us pinpoint the PS1-10jh black hole's mass to $(2.8 \pm 0.1) \times 10^6\ M_\odot$.

Spinning black holes

A TDE can also tell us about the spin of the responsible SMBH. As we saw in figure 2, the Schwarzschild radius R_S of a black hole becomes equal to the R_T of a Sun-like star at an M_{BH} of about $10^8\ M_\odot$. The event horizon of a spinless black hole is at R_S, and nothing that happens inside the event horizon can be seen by an outsider.

But the event horizon shrinks with increasing black hole angular momentum J. At $J = GM_{BH}^2/c$, the maximum allowed by general relativity, the event horizon has shrunk to $R_S/2$. For maximally spinning SMBHs, the event horizon does not reach R_T for Sun-like stars until M_{BH} reaches $7 \times 10^8\ M_\odot$. So if we see a Sun-like star being disrupted by a black hole heavier than $10^8\ M_\odot$, we know that the SMBH must be spinning.

Another consequence of SMBH spin in a TDE may be the powering of a transient jet of high-energy material and radiation out along the axis of the ephemeral accretion disk formed by the stellar debris. Steady-state radio synchrotron radiation from persistent, powerful jets is observed in about 10% of all active galactic nuclei (AGNs)—galaxies whose central SMBHs feed vigorously and steadily on gas from a large accretion disk. The x-ray emission from AGNs is generated by radiation from gas viscously heated in the accretion process.

It's conjectured that AGN jets are powered by rotational energy extracted from a spinning SMBH via a magnetic field that's wound (the short way) around the donut-shaped accretion disk.[9] Similarly but on a smaller scale, a TDE might launch a transient jet if the star was disrupted by a spinning SMBH, assuming that the new accretion disk formed by the returning stellar debris has a strong enough magnetic field. Exciting new observations favor such a scenario, but theorists have not yet worked out TDE jet formation in detail. In any case, the transient jet from a TDE could be used to probe the previously undisturbed environment of a quiescent SMBH through the interactions of the jet as it propagates outward.[5,10]

Looking down the barrel

The 18 or so TDE candidates that have been discovered to date in soft-x-ray, UV, and optical surveys have been broadly consistent with theoretical predictions for radiation from a newly formed accretion disk of stellar debris around an SMBH, with

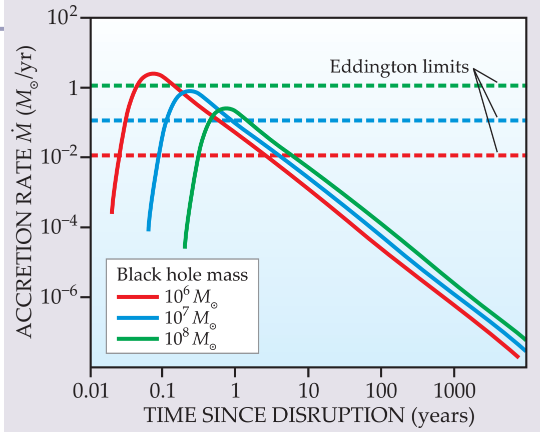


Figure 3. The accretion rate onto a supermassive black hole (SMBH) of debris from a star's disruption by that SMBH is plotted for different black hole masses M_{BH} as a function of time t. With increasing M_{BH}, rise time to peak accretion increases, but the peak accretion rate decreases. For the lighter black holes, the peak accretion rate surpasses the Eddington limit, above which the accretion is likely to generate collimated jets of outflowing material and radiation. At late times, the accretion rates exhibit the $t^{-5/3}$ decay expected for the range of eccentric Keplerian orbits of the gravitationally bound debris. (Adapted from ref. 5.)

peak luminosities close to the Eddington limits for black hole masses of 10^6–$10^7\ M_\odot$. But a new class of "relativistic" TDEs with very different properties has emerged from all-sky monitoring by NASA's *Swift* hard-x-ray telescope (see figure 5).

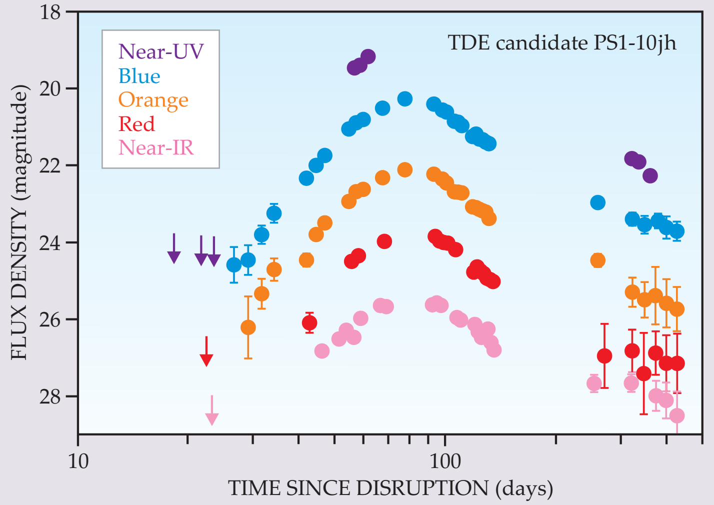
Swift has discovered two hard-x-ray outbursts peaking at luminosities far above the Eddington limits, each accompanied by brightening synchrotron emission detected in prompt follow-ups with radio telescopes. One of the *Swift* events, recorded in 2011, was spatially and temporally coincident with the near-IR flaring of a very distant (4×10^9 light-years) galactic nucleus recorded by the *Hubble Space Telescope*.[11]

The extreme luminosities of both *Swift* events, combined with their spectral distributions from radio to hard x rays, were interpreted as beamed emission seen by looking down the barrels of transient, ultrahigh-velocity jets of stellar debris.[12] Neither host galaxy had shown previous evidence of accretion activity onto its central black holes, and the x-ray light curves faded at rates consistent with the fallback of TDE debris. It's likely, therefore, that both events involved jets generated by stellar tidal disruptions.[13] Because the TDE jets are thought to be highly collimated, seeing one head-on should be a rare treat.

TDEs provide a cosmic laboratory for studying the formation of accretion disks and jets in real time. There are still important theoretical hurdles: How does stellar debris falling back onto the SMBH from highly eccentric orbits eventually circularize and form an accretion disk that feeds the black hole through viscous transport of angular momentum? Several mechanisms have been proposed to drive the circularization; the most promising is general-relativistic precession of orbits.[14]

Another challenging problem is to understand

Figure 4. The optical flare of this candidate tidal-disruption event (TDE) was discovered in 2010 by the Pan-STARRS telescope in Hawaii two months before it peaked. Through a range of optical filters, the telescope recorded the flare for more than a year. (Arrows are upper limits.) The *GALEX* orbiter contributed early and late measurements in the near-UV. At late times, all the light curves show fading similar to the $t^{-5/3}$ decay expected of TDEs. Magnitude is an inverse logarithmic measure of apparent brightness. For clarity, the optical light curves are offset downward. (Adapted from ref. 8.)



how the accretion rate translates into the radiated emission detected by telescopes. The luminosity and spectrum of a TDE have not been rigorously calculated with codes that take account of both hydrodynamics and radiative transport. There are already significant discrepancies between the observed spectral distributions of TDEs and models that assume, for simplicity, that transient TDE accretion disks look much like their larger, steady-state AGN cousins.

Figure 3 shows that for SMBHs with masses less than $10^7\ M_\odot$, accretion rates near peak luminosity are likely to exceed the Eddington limit. At super-Eddington accretion rates, the resulting radiation either generates powerful outflowing winds or is carried into the black hole with the gas.[15] Observations of TDEs should provide a unique test bed for super-Eddington accretion models applicable to black hole systems in general. Measuring the fraction of TDEs that produce jets, with follow-up radio and hard-x-ray observations, should also shed light on the conditions necessary for jet formation in TDEs and AGNs.

Demographics with large samples

It's now clear that TDE searches can probe the demographics of SMBHs and their neighboring stellar populations in very distant galaxies. The future workhorse surveys will be wide-field, high-cadence monitoring at optical wavelengths. The most promising of such projects is the Large Synoptic Survey Telescope (LSST) to be based in Chile (see PHYSICS TODAY, September 2012, page 22). Construction, funded by NSF and the Department of Energy, is scheduled to begin this year. The LSST will have about 30 times the TDE survey power of existing facilities. It's designed to survey half the sky per night with high sensitivity. Accumulating thousands of detailed TDE light curves, the LSST should make possible the statistical study of TDEs as a function of host-galaxy type, cosmological age, and SMBH mass.

Large samples of TDEs have the potential to reveal the extremes of the SMBH population, from $10^8\ M_\odot$ spinning SMBHs, to black holes lighter than $10^6\ M_\odot$, the so-called intermediate-mass black holes (IMBHs). Neglecting spin effects, one would expect a sharp cutoff in the TDE rates beyond $10^8\ M_\odot$. But taking into account that SMBHs are spun up during their growth over cosmic time,[16] one anticipates a tail of TDEs from spinning SMBHs heavier than $10^8\ M_\odot$.

We also expect TDEs from IMBHs, the proposed missing evolutionary link between stellar black holes and SMBHs. In particular, IMBHs of masses below $10^4\ M_\odot$ have tidal fields strong enough to disrupt white dwarfs—the oxygen-rich compact remnants of evolved Sun-like stars. The tidal disruption of a white dwarf could trigger a thermonuclear explosion similar to a type Ia supernova.[17] A peculiar type Ia supernova accompanied by a TDE in the nucleus of a dwarf galaxy or globular cluster would be the smoking-gun signature of an IMBH. Large enough samples of TDEs should make possible the study of rare and exotic objects such as coalescing binary SMBH systems and their recoiling merger remnants.

Impostors

To assemble large samples of TDEs from monitoring surveys, one has to filter out the much more common populations of supernovae and variable AGNs.

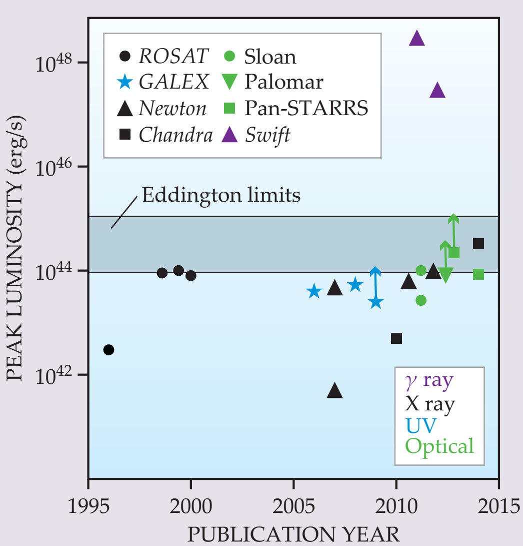


Figure 5. The peak luminosities of the 20 candidate tidal-disruption events (TDEs) discovered to date by ground-based and orbiting telescopes. Arrows indicate upper limits. The shaded region shows the range of Eddington upper limits on luminosity for black holes with masses ranging from 10^6 to 10^7 solar masses. Only the two TDE candidates discovered in hard-x-ray flares by the *Swift* orbiter peak well above the Eddington limits, suggesting highly beamed radiation in our direction from jets of stellar debris boosted to relativistic velocities.

Supernovae do generally have distinctive spectral evolution, and they're not restricted to the immediate vicinity of the galactic nucleus. But still, they're a hundred times more common than TDEs. So one has to expect a significant population of supernovae with nonstandard spectra masquerading as TDEs.

The spectra of variable AGNs, on the other hand, look a lot like those of TDEs. But their variability is stochastic, and it's generally characterized by longer time scales. The LSST's anticipated 10-year working lifetime should effectively minimize the AGN contamination of its TDE harvest.

Optical photometry alone is not enough. Rapid follow-up observations across the electromagnetic spectrum are essential for efficient identification and characterization of TDEs. Most of the energetic radiation from a TDE is expected to be in the UV and soft x rays. Jetted emission is likely to produce radio synchrotron emission and, when the jet is along our line of sight, hard-x-ray emission. Future space-based observatories in "co-observing" modes with the LSST could cover all the photon-energy regimes and thus constrain a TDE's total radiant output.

Future hard-x-ray survey telescopes such as the European Space Agency's proposed Large Observatory for X-Ray Timing mission will be particularly sensitive to jetted TDEs. Follow-up spectroscopic observations are also critical for looking for gas that might reveal the composition of the disrupted star and trace the geometry and dynamics of the stellar debris. High-cadence optical light curves, augmented by spectra and multiwavelength observations, can provide an extraordinarily complete picture of a TDE, from the mass of the black hole to the amount of debris it swallows.

With the large samples expected in the next decade, astrophysicists can continue to test models of black hole accretion and jet formation and to map out the demographics of the ubiquitous but heavily veiled supermassive black holes.

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