Star-Shredding Black Holes

Dormant black holes turn into ravenous beasts when renegade stars wake them from their slumber.


Suvi Gezari

The unlucky star that wanders too close to a supermassive black hole faces a catastrophic end. Initially, it bulges slightly due to tidal forces, just as Earth's oceans bulge in response to the Moon's gravity. Over the next half hour or so, increasing gravitational stress rips the star apart. Stellar remains spread in a wide spiral; the gas that isn't ejected at high speeds circles back to feed the black hole, glowing bright-hot before it disappears into its gaping maw.

The stellar remains not ejected at high speeds circle back, glowing bright-hot before they disappear into the black hole's gaping maw.

Astronomers first proposed that stars could become victim to tidal shredding by black holes in 1975, but it took two decades for astronomers to observe the first convincing candidates. In the past five years, two developments have substantially widened the discovery potential. First, we have found several events emitting light at optical wavelengths, where the next, most powerful surveys will soon scan the sky for transient and variable phenomena. And astronomers have also detected X-rays and radio waves from brief, spectacular jets that can form when the shredded star funnels into the black hole. These developments are guiding future searches for these rare events.

We can see black holes despite what their name suggests because when they devour a meal, they become beacons of light. Snared gas releases its gravitational potential energy as light and heat, rendering black holes visible even when they're billions of light-years away. In luminous *active galactic nuclei*, huge disks of gas feed supermassive black holes millions or billions of times the mass of our Sun. Such long-lasting meals can power jets of material traveling close to the speed of light and stretching a million light-years through space.

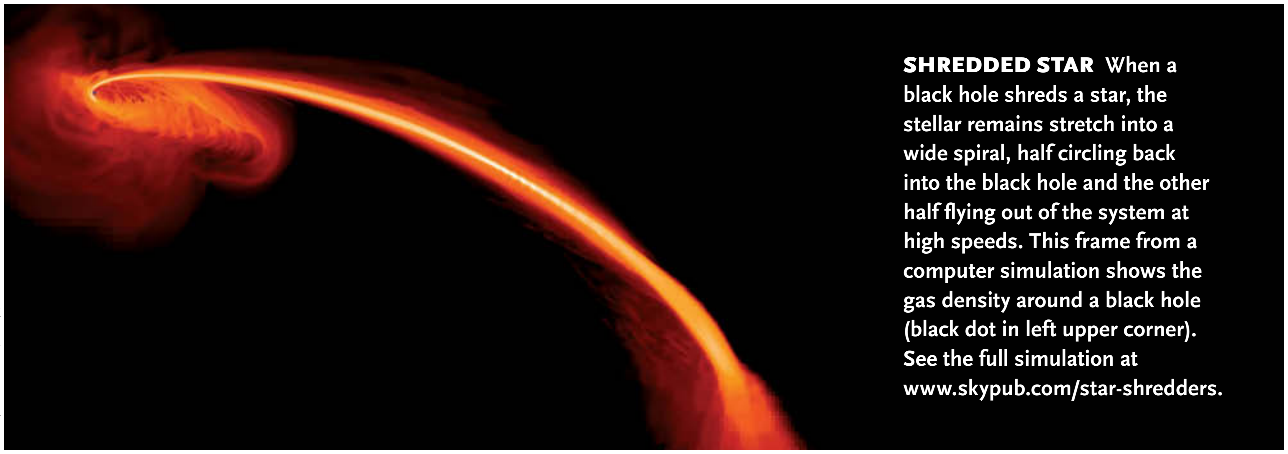
But active galaxies are in the minority — most galaxies' black holes hibernate, dormant for lack of fuel. Their presence can only be inferred by the rapid orbits of stars and gas clouds within their "sphere of influence," which extends out to 30 light-years for black holes 100 million times more massive than the Sun. Telescopes have resolved this sphere in 30 or so nearby galaxies, but in more distant galaxies we only see the slumbering leviathans if they wake for a bite to eat.

A Tidal Rip

Black holes shred stars using the same force that governs the tides. When the Moon's gravity pulls on Earth, it tugs harder on the nearside than on the farside: the nearside oceans feel a stronger pull than Earth's core, which feels a stronger pull than the oceans on the farside. As a result, Earth stretches into a slightly oblong shape, with high

Illustration by Casey Reed

Supermassive black holes sleep quietly in the hearts of distant galaxies. But they remain invisible only as long as there's nothing to eat. This illustration shows a rare close-passing star sacrificing itself to briefly reveal the black hole's presence.



NASA / S. GEZARI (JHU) / JAMES GUILLOCHON (UCSC)

SHREDDED STAR When a black hole shreds a star, the stellar remains stretch into a wide spiral, half circling back into the black hole and the other half flying out of the system at high speeds. This frame from a computer simulation shows the gas density around a black hole (black dot in left upper corner). See the full simulation at www.skypub.com/star-shredders.

tides on the sides facing and opposite the Moon. The same effect occurs when a star ventures too close to a black hole, but the pull on the nearside is so much stronger than on the farside that the tidal bulge literally tears the star apart.

The tidal tug-of-war pits the black hole's gravity against the self-gravity holding the star together. The match tips in the black hole's favor at a critical distance determined by the mass and size ratios of the black hole relative to the star. If our Sun approached a black hole a million times its mass, that critical distance would be half the Earth-Sun distance, or 0.5 astronomical unit (a.u.).

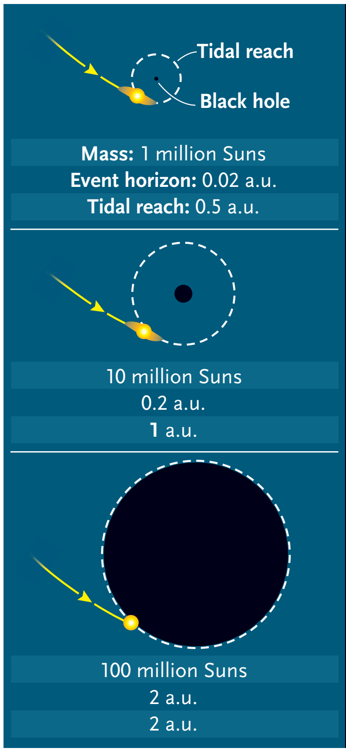
As the mass of the black hole increases, its tidal reach grows more slowly than its event horizon, the boundary from within which even light cannot escape. For a black hole with the mass of 100 million Suns, both the tidal reach and the event horizon extend to 2 a.u. Black holes this massive gulp their stars whole — the star passes through the event horizon before it ever feels a stretch.

But there's a loophole. Even at higher masses, it's possible for a black hole to shred rather than gulp a star — as long as the black hole is spinning. Einstein's general theory of relativity predicts smaller event horizons for quicker spins; the fastest-whirling have event horizons half the size of their nonspinning cousins. A spinning black hole could have a mass of up to 700 million Suns and still shred a Sun-like star outside its event horizon.

Astronomers have never directly measured a black hole's spin, though considerable indirect evidence suggests many do spin (*S&T:* May 2011, page 20). But we can definitively say we've found a spinning black hole if we observe a leviathan with more than 100 million solar masses rip apart and consume a Sun-like star.

Tidal-shredding events can also provide a smoking gun for intermediate-mass black holes (IMBHs) 1,000 to 100,000 times the mass of the Sun. Although there's some evidence that IMBHs lurk in the centers of dwarf galaxies and star clusters, their existence remains controversial.

IMBHs could shred objects much denser than stars, such as the stellar remnants known as white dwarfs. Although a supermassive black hole would swallow a white dwarf whole, an IMBH is small enough to tear a white dwarf apart while it still lies outside the event horizon. The shredding could trigger thermonuclear burning, causing an explosion similar to a Type Ia supernova. Direct evidence for the presence of an IMBH could come from a peculiar supernova in the center of a dwarf galaxy or star cluster.



S&T: LEAH TISCIONE

Tidal Reach

A black hole's strong gravitational pull overcomes a star's self-gravity at a critical distance known as its tidal reach. But as a black hole's mass increases, its tidal reach grows more slowly than its event horizon, the radius from within which light cannot escape. So nonspinning black holes with masses above 100 million Suns will swallow stars whole.

Messy Meals

A black hole small enough to shred its meal outside the event horizon will gobble it down like a ravenous beast, flinging half the stellar debris out of the system at high speeds. The other half eventually spirals around, flaring as it falls into the gravitational well. More massive black holes tear stars apart at greater distances, so the stellar debris takes longer to fall in. This fall-back time can be used to "weigh" the central black hole. We estimate black hole mass by combining measurements of the changing brightness with simulations to determine how quickly the bound stellar debris returned to the black hole.

The number of stars passing near a central black hole ought to diminish over time. But the nucleus of a galaxy is a crowded place and random interactions between stars scatter stars into new orbits, replenishing the black hole's metaphorical cookie jar. Detailed calculations balancing these two processes estimate that a black hole will scarf down one star every 1,000 to 100,000 years.

We can't wait around that long for a star to approach the supermassive black hole closest to home — the one lurking in the Milky Way's center. But later this year, we might see the next best thing, when our neighborhood bully is expected to tear into a passing gas cloud (see page 23). Moreover, we now have powerful telescopes surveying millions of galaxies over wide swaths of sky, guaranteeing that we'll see star-shredding action in the distant universe.

The Search Is On

Astronomers discovered the first candidate black-hole-shredded stars, dubbed *tidal-disruption events*, using the ROSAT satellite, which was launched in 1990 to survey the low-energy X-ray sky (100 to 2,000 electron volts). A decade after the launch, astronomers analyzing the

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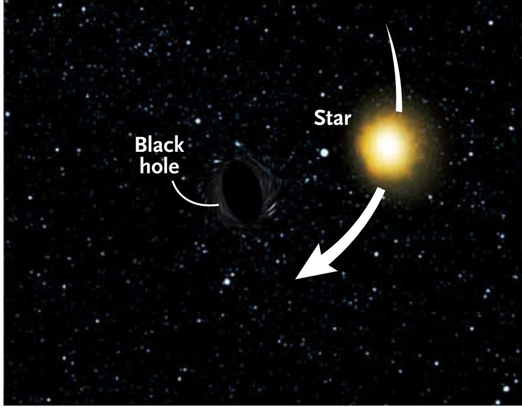
satellite's vast database noticed several otherwise normal galaxies that had briefly flared in X-rays.

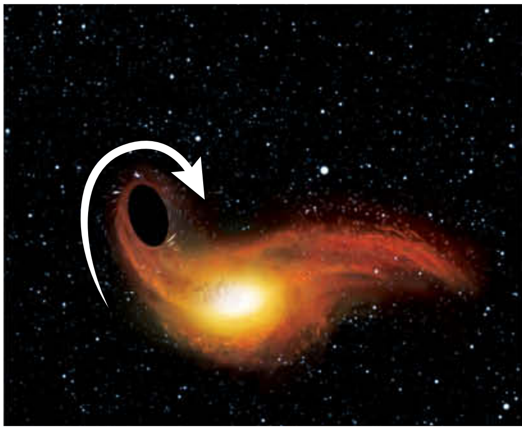
Follow-up observations from the Hubble Space Telescope confirmed these were not active galaxies — the central black hole had been truly dormant before the mysterious X-ray bursts appeared. And Chandra X-ray Observatory images taken 10 years after the initial flares showed that the X-rays had indeed faded away over time. In contrast to the theoretical research described above, calculations based on eight years of ROSAT observations show that a galaxy's central black hole might gobble a close-passing star every 100,000 years or so.

The Chandra and XMM-Newton X-ray satellites continue to find additional candidates with properties similar to the ROSAT-discovered flares. A black hole's brief, star-fueled feeding frenzy explains the rate and other properties of the X-ray flares. But their discovery years after the

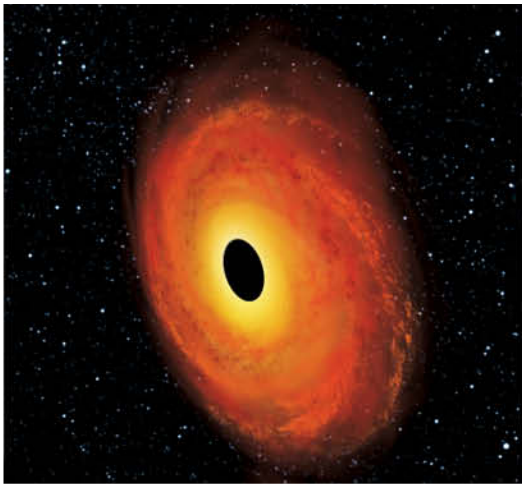
Black Hole Eats Star



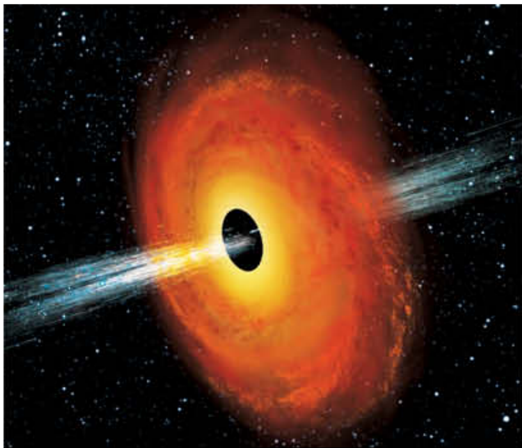
1. A star passes too close to a supermassive black hole.



2. The black hole's gravitational pull tears the star apart.



3. Half the stellar remains stream toward the black hole, forming a brightly glowing disk by which astronomers can detect the event.



4. Magnetic fields near the black hole can power a jet of particles moving near the speed of light. Viewed head-on, this jet is a powerful radio and X-ray source.

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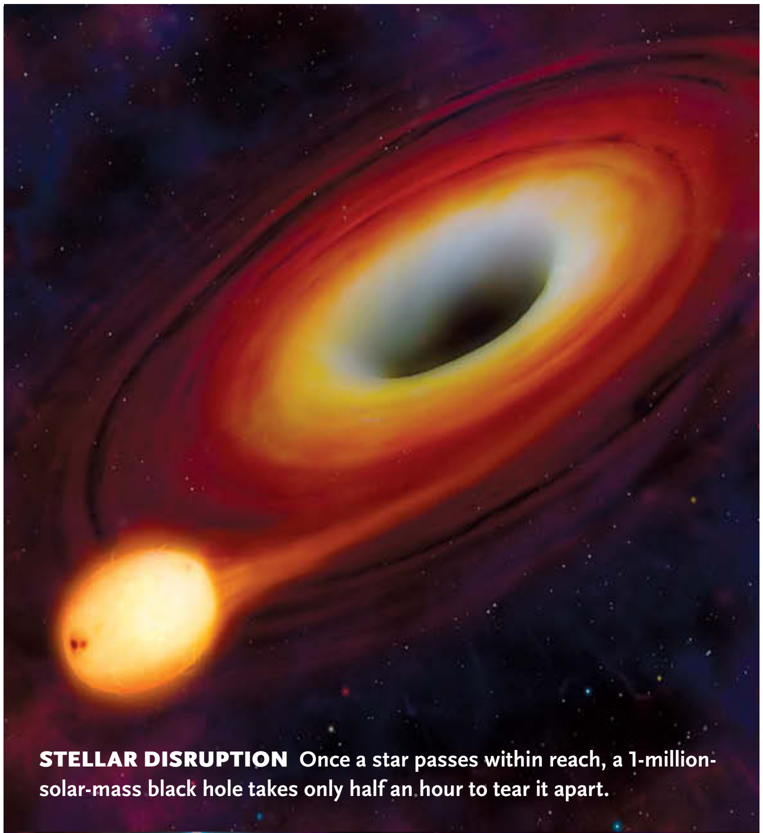

STELLAR DISRUPTION Once a star passes within reach, a 1-million-solar-mass black hole takes only half an hour to tear it apart.

CONSEQUENCES The optical and ultraviolet flares occur many months later, after the stellar remains have spiraled inward. This artist's conception includes a relativistic jet powered by the gaseous disk.

UNIVERSITY OF WARWICK / MARK GARLICK (2)

initial outbursts limits further study.

Understanding these transient events requires catching them in action. When a supermassive black hole chows down on tidally disrupted debris, the temperature of the inspiraling gas can climb to 1 million degrees C (1.8 million degrees F). Most of the light is emitted as X-rays, but a tail of emission extends to longer, ultraviolet and optical wavelengths. The Galaxy Evolution Explorer (GALEX), a space telescope launched in 2003, observes ultraviolet radiation, which Earth's atmosphere blocks from ground-based scopes. NASA designed GALEX's wide-field imaging capability to study galaxies' star-formation history, but I realized we could use the wide-field instrument to search among hundreds of thousands of galaxies to find tidal disruption events as they happen.

GALEX repeatedly observed patches of sky over a three-year period to create images with long exposure times and deep sensitivity. My team examined these fields and identified three luminous ultraviolet flares coming from otherwise normal-looking galaxies. The same flares appeared simultaneously in visible-light observations taken as part of the Canada-France-Hawaii Telescope (CFHT) Legacy Survey.

Combining ultraviolet and visible-light information, we found the three flares came from gas glowing at temperatures greater than 50,000°C, almost 10 times as hot as the Sun's visible surface. The gas remained hot for the duration of the flare, which faded according to theoretical predictions for shredded stellar debris accreting onto a black hole. Chandra X-ray observations showed that the flares were faint in high-energy X-rays, so ongoing accretion in active galaxies can't explain these events.

A search of archival data from the Sloan Digital Sky Survey (SDSS), a visible-light study of more than a quarter

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of the sky, revealed two additional tidal-disruption candidates. In these events, flaring gas glowed at temperatures greater than 20,000°C. Their light faded in the same way as the transients discovered in the GALEX images, with the gas remaining hot over time. But the observations weren't frequent enough to estimate how long the flare took to reach its peak brightness, information that would have allowed us to estimate the black hole mass.

We discovered a sixth candidate by combining the GALEX survey with simultaneous observations from Pan-STARRS 1, a 1.8-meter telescope on the summit of Haleakalā, Hawaii, that scans the northern sky for visible-light transients. In June 2010 these telescopes caught a

To see video animations of star-shredding black holes, go to **skypub.com/star-shredders**.

flare at the center of a distant galaxy and monitored the outburst as it brightened to a peak a month later before fading away over the following year.

This time, we could model the changing brightness using tidal disruption simulations; we estimated a mass of 2 million Suns for the central black hole. More surprising was the nature of the star it had captured.

The stellar debris consisted of fast-moving helium stripped of its electrons — surprisingly, there was no accompanying hydrogen. This is odd, since stars are usually made mostly of hydrogen and only a little helium. Before it met an untimely end, this star had already lost its outer layers, exposing its helium core. Very massive and short-lived stars can lose their hydrogen envelopes through winds, but the host galaxy's stars are too old and long-lived for winds to be the culprit.

More likely, the star had lost its hydrogen envelope during a previous pass around the black hole (*S&T*: Aug. 2012, page 12). A star near the end of its life might have bloated into the red giant phase, which would have made it more vulnerable to tidal stripping. Other studies suggest this star was not one of a kind — red giants stripped of their hydrogen envelopes are likely to dominate the stellar population near a supermassive black hole.

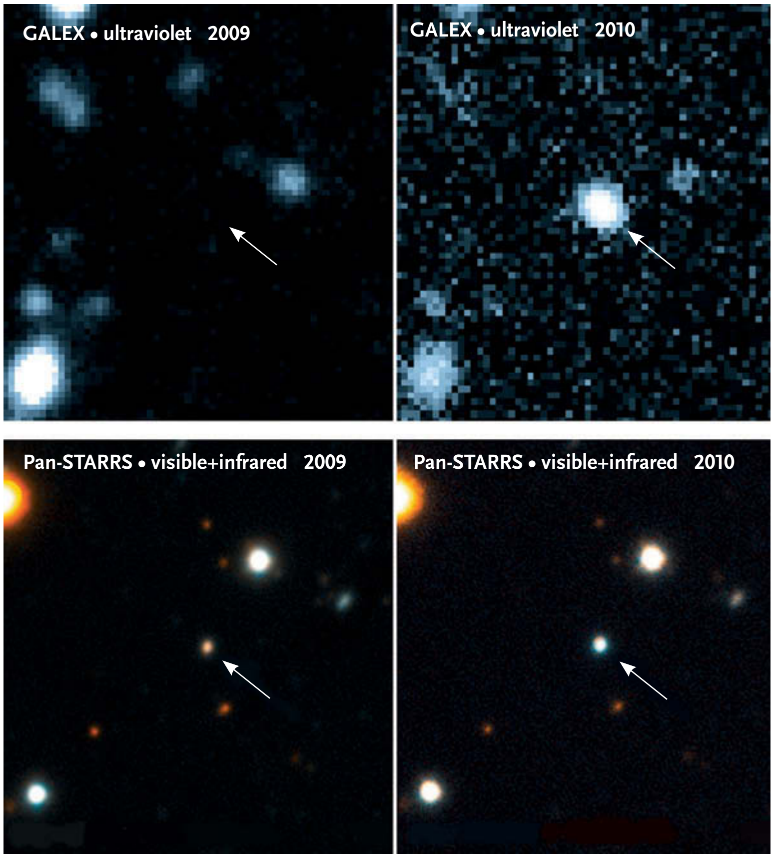
The Birth of a Jet

The discovery of Sw J164449.3+573451 in March 2011 heralded a major paradigm shift in the search for tidal-disruption events. At first astronomers mistook this flare for a gamma-ray burst whose X-ray glow ought to have lasted for minutes. But when the flare continued for more than a week, it became clear that this event was something completely different.

High-resolution follow-up images from the Gemini North Telescope on Mauna Kea, Hawaii, and the Very Large Array, a radio observatory in New Mexico, placed the flare within the host galaxy's nucleus. This position strongly suggests that the nature of the flare has something to do with the central black hole. The black hole's mass, estimated to be 10 million solar masses given the galaxy's size, is in the right range to tidally disrupt a star. And archival X-ray observations showed that it had been dormant before the flare occurred.

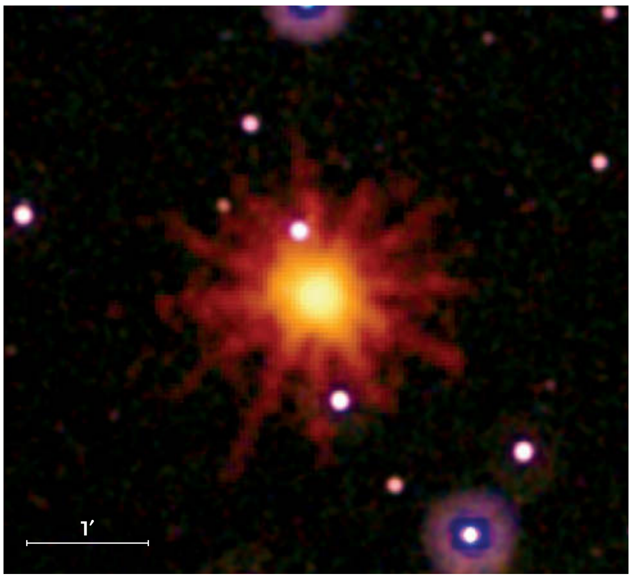
But that's where the agreement between theory and observation ends. Observations measured the flare's X-ray luminosity to be 100 times brighter than the maximum output allowed for a black hole of that mass. Above this maximum, the pressure from the radiation ought to blow away the accreting gas and shut off the flare.

One way to explain this apparent contradiction is if the shredded star fuels an ultra-speedy jet. Special relativis-



NASA / S. GEZARI (JHU) / ARMIN REST (STSCI) / RYAN CHORNOCK (CFA)

BEFORE AND AFTER The GALEX satellite and Pan-STARRS 1 telescope caught a flare in ultraviolet and optical light, respectively, from a galaxy 2.7 billion light-years away. The outburst shows the distinct signatures of a black hole tidally shredding a helium-rich star.



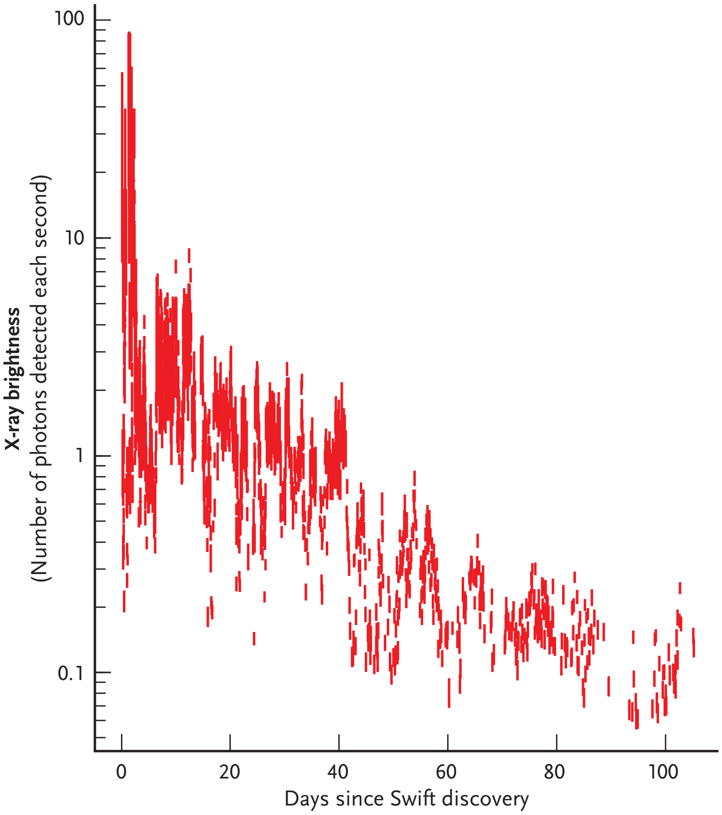
NASA / CXC / MIT / F. BAGANOFF, R. SHCHERBAKOV ET AL

TIDAL FLARE The Swift satellite spots an intense X-ray flare (yellow and red) from a tidal-disruption event known as Sw J1644. X-rays penetrated the heavy dust cover that hides the corresponding optical and ultraviolet light (white and purple) from view.

tic effects in the fast-flowing material would amplify the radiation observed. Rapidly brightening radio emission confirmed that material is indeed moving close to the speed of light, so the most likely explanation for Sw J1644 is that the inward-spiraling stellar debris from a tidal-disruption event powered a relativistic jet pointed our way.

Do all shredded stars fuel jets? Probably not — we would have detected jet signatures in other tidal-disruption events had they been present. One barrier to forming jets is generating the necessary magnetic field; stellar magnetic fields aren't strong enough on their own. The field fueling Sw J1644's jet must have come from somewhere else, such as from instabilities in the newly formed accretion disk feeding the black hole. Astronomers continue to monitor Sw J1644 at radio wavelengths to watch what happens as the jet plows through the ambient gas surrounding the feeding black hole.

Unfortunately, corresponding optical and ultraviolet studies of the accretion disk are impossible because dust hides the black hole from view. But there are other ways of learning about the stellar debris as it swirls into the black hole. Rubens Reis (University of Michigan) reported in the August 2, 2012, *Science* the discovery of a 200-second



FADING LIGHT **Swift's X-ray Telescope observed Sw J1644 for three months after the first flare on March 28, 2011. The light faded over time as the black hole gobbled the shredded star.**

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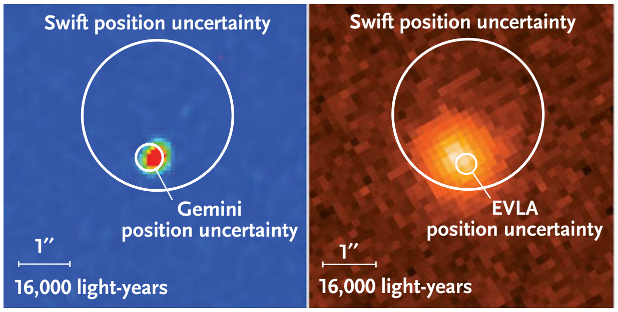

NASA / SWIFT / STEFAN IMMLER

LOCATING A FLARE **The Swift satellite's position uncertainty is too large to precisely locate the X-ray flare named Sw J1644. But the high-resolution Expanded Very Large Array image (*left*) located the simultaneous radio flare: it was coming from a distant galaxy's nucleus, imaged by the Gemini North Telescope in Hawaii (*right*). A nuclear outburst of this magnitude hints that the central supermassive black hole was involved.**

periodic signal in Sw J1644's light curve (*S&T*: Nov. 2012, page 14). This period corresponds to the orbit of material around the black hole, tantalizing evidence that ties the jet to the accretion of stellar debris.

Just two months after Sw J1644's discovery, a team led by Bradley Cenko (University of California, Berkeley) detected a similar event called Sw J2058. This time, observations show evidence of a flare both from the swirling stellar debris and from a relativistic jet, so astronomers will be able to study both processes in the same system.

The future is bright for transient searches. Several ground-based surveys are in the works, including the Large Synoptic Survey Telescope (LSST), which plans to photograph the entire available sky twice each week once it goes online early next decade. LSST could potentially discover thousands of shredding events per year. Astronomers have proposed additional surveys with wide-field X-ray telescopes, such as the eROSITA instrument to be launched in 2014 aboard a Russian satellite.

In just a few years, the hundredfold or so increase in number of detections will make it possible to study tidal shredding events en masse. We can then use the light from these feeding frenzies to weigh galaxies' central black holes over cosmic time and piece together the history of black hole growth.

Since visible light, radio waves, and X-rays each reveal a different view of the star-shredding process, following up on discoveries with observations across the electromagnetic spectrum will be key. Only then can we turn tidal-disruption events into cosmic laboratories, which provide our only direct view of the mysterious beasts slumbering in the hearts of distant galaxies. ✦

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