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Astronomers observe evolution of a black hole as it wolfs down stellar material

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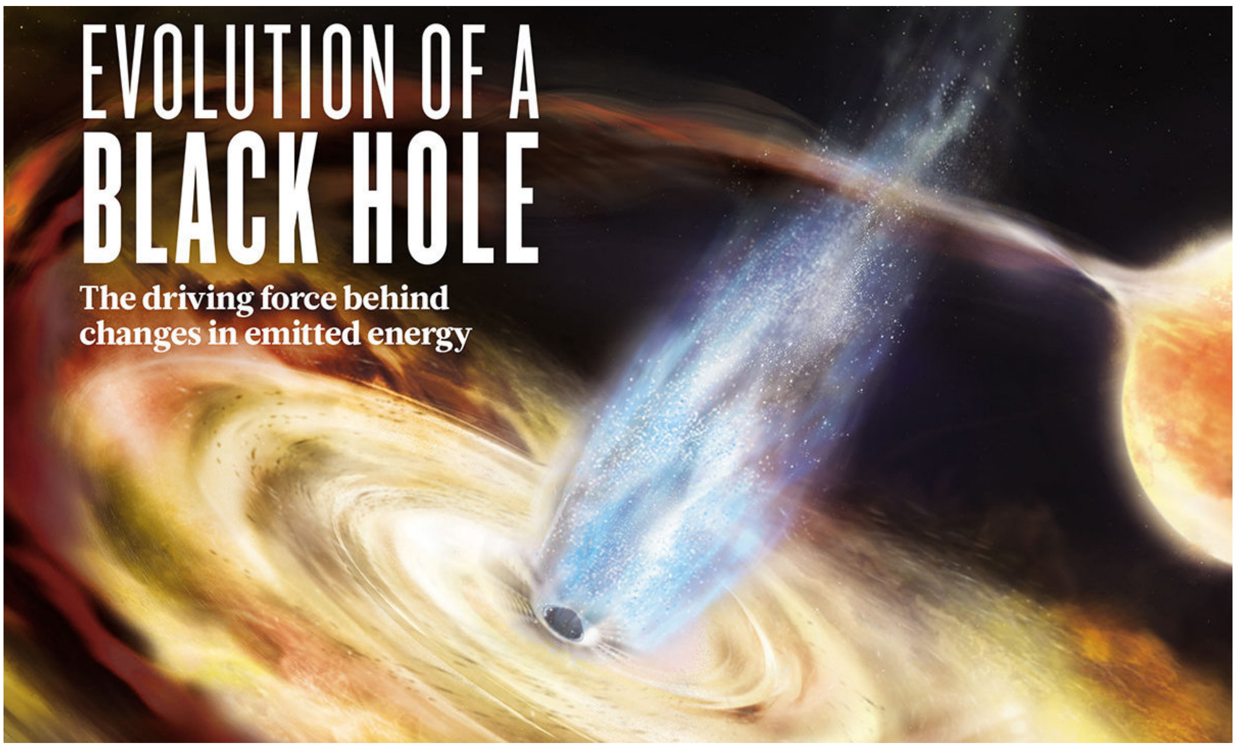

Cover for 09 January *Nature*. Credit: Aurore Simonnet and *Nature*.

On March 11, an instrument aboard the International Space Station detected an enormous explosion of X-ray light that grew to be six times as bright as the Crab Nebula, nearly 10,000 light years away from Earth. Scientists determined the source was a black hole caught in the midst of an outburst—an extreme phase in which a black hole can spew brilliant bursts of X-ray energy as it devours an avalanche of gas and dust from a nearby star.

Now astronomers from MIT and elsewhere have detected "echoes" within this burst of X-ray emissions, that they believe could be a clue to how black holes evolve during an outburst. In a study published today in the journal *Nature*, the team reports evidence that as the black hole consumes enormous amounts of stellar material, its corona—the halo of highly-energized electrons that surrounds a black hole—significantly shrinks, from an initial expanse of about 100 kilometers (about the width of Massachusetts) to a mere 10 kilometers, in just over a month.

The findings are the first evidence that the corona shrinks as a black hole feeds, or accretes. The results also suggest that it is the corona that drives a black hole's evolution during the most extreme phase of its outburst.

"This is the first time that we've seen this kind of evidence that it's the corona shrinking during this particular phase of outburst evolution," says Jack Steiner, a research scientist in MIT's Kavli Institute for Astrophysics and Space Research. "The corona is still pretty mysterious, and we still have a loose understanding of what it is. But we now have evidence that the thing that's evolving in the system is the structure of the corona itself."

Steiner's MIT co-authors include Ronald Remillard and first author Erin Kara.

X-ray echoes

The black hole detected on March 11 was named MAXI J1820+070, for the instrument that detected it. The Monitor of All-sky X-ray Image (MAXI) mission is a set of X-ray detectors installed in the Japanese Experiment Module of the International Space Station (ISS), that monitors the entire sky for X-ray outbursts and flares.

Soon after the instrument picked up the black hole's outburst, Steiner and his colleagues started observing the event with NASA's Neutron star Interior Composition Explorer, or NICER, another instrument aboard the ISS, which was designed partly by MIT, to measure the amount and timing of incoming X-ray photons.

"This boomingly bright black hole came on the scene, and it was almost completely unobscured, so we got a very pristine view of what was going on," Steiner says.

A typical outburst can occur when a black hole sucks away enormous amounts of material from a nearby star. This material accumulates around the black hole, in a swirling vortex known as an accretion disk, which can span millions of miles across. Material in the disk that is closer to the center of the black hole spins faster, generating friction that heats up the disk.

"The gas in the center is millions of degrees in temperature," Steiner says. "When you heat something that hot, it shines out as X-rays. This disk can undergo avalanches and pour its gas down onto the central black hole at about a Mount Everest's worth of gas per second. And that's when it goes into outburst, which usually lasts about a year."

Scientists have previously observed that X-ray photons emitted by the accretion disk can ping-pong off high-energy electrons in a black hole's corona. Steiner says some of these photons can scatter "out to infinity," while others scatter back onto the accretion disk as higher-energy X-rays.

By using NICER, the team was able to collect extremely precise measurements of both the energy and timing of X-ray photons throughout the black hole's outburst. Crucially, they picked up "echoes," or lags between low-energy photons (those that may have initially been emitted by the accretion disk) and high-energy photons (the X-rays that likely had interacted with the corona's electrons). Over the course of a month, the researchers observed that the length of these lags decreased significantly, indicating that the distance between the corona and the accretion disk was also shrinking. But was it the disk or the corona that was shifting in?

To answer this, the researchers measured a signature that astronomers know as the "iron line"—a feature that is emitted by the iron atoms in an accretion disk only when they are energized, such as by the reflection of X-ray photons off a corona's electrons. Iron, therefore, can measure the inner boundary of an accretion disk.

When the researchers measured the iron line throughout the outburst, they found no measurable change, suggesting that the disk itself was not shifting in shape, but remaining relatively stable. Together with the evidence of a diminishing X-ray lag, they concluded that it must be the corona that was changing, and shrinking as a result of the black hole's outburst.

"We see that the corona starts off as this bloated, 100-kilometer blob inside the inner accretion disk, then shrinks down to something like 10 kilometers, over about a month," Steiner says. "This is the first unambiguous case of a corona shrinking while the disk is stable."

"NICER has allowed us to measure light echoes closer to a stellar-mass black hole than ever before," Kara adds. "Previously these light echoes off the inner accretion disk were only seen in supermassive black holes, which are millions to billions of solar masses and evolve over millions of years. Stellar black holes like J1820 have much lower masses and evolve much faster, so we can see changes play out on human time scales."

While it's unclear what is exactly causing the corona to contract, Steiner speculates that the cloud of high-energy electrons is being squeezed by the overwhelming pressure generated by the accretion disk's in-falling avalanche of gas.

The findings offer new insights into an important phase of a black hole's outburst, known as a transition from a hard to a soft state. Scientists have known that at some point early on in an outburst, a black hole shifts from a "hard" phase that is dominated by the corona's energy, to a "soft" phase that is ruled more by the accretion disk's emissions.

"This transition marks a fundamental change in a black hole's mode of accretion," Steiner says. "But we don't know exactly what's going on. How does a black hole transition from being dominated by a corona to its disk? Does the disk move in and take over, or does the corona change and dissipate in some way? This is something people have been trying to unravel for decades And now this is a definitive piece of work in regards to what's happening in this transition phase, and that what's changing is the corona."

More information: E. Kara et al. The corona contracts in a black-hole transient, *Nature* (2019). DOI: 10.1038/s41586-018-0803-x

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