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Physicists reconstruct the collision that launched a runaway black hole

In September 2022, astronomers noticed a perplexing feature on an image of a galaxy around 7.5 billion light-years from Earth. A thin line stretching over 202,000 light-years pointed directly away from the galaxy's center. Its leading edge was an unresolved point, with no detectable stars, speeding away at nearly 1,000 kilometers per second.

The scientists who spotted it interpreted the feature as a super-massive black hole plowing through intergalactic space, triggering star formation in its wake. Now researchers from UC Santa Barbara and University of Texas at Austin have published a paper on the violent event that could have shot this behemoth from its host galaxy.

The findings, published in Physical Review Letters, provide the first account of a class of black hole mergers predicted by general relativity, and will help scientists prepare for the next generation of gravitational wave observatories.

A spectacular collision

Merging black holes produce strong gravitational waves as the massive objects warp spacetime and spiral into each other. If the system is lopsided, these waves can generate enough of a kick to launch the newly formed, larger black hole in an entirely different trajectory, “like the recoil of a fired cannon,” said co-author Tejaswi Venumadhav, an associate professor in UCSB’s Department of Physics.

The authors of a previous paper had named the black hole they observed RBH-1. And after scoping out the scene, they proposed that it was hurtling into intergalactic space.

Venumadhav and his co-authors picked up where their colleagues left off, working backward like forensic detectives reconstructing a collision from the debris and tire tracks. They simulated hundreds of thousands of hypothetical black-hole pairs, computed the recoil each would have produced, and kept only those matching the speed of RBH-1.

The simulations revealed that the parent black holes would’ve been similar sizes, with one at most six times as massive as the other. That said, the recoil from even a large merger would have topped out around 200 km/s, far short of the breakneck 1,000 km/s astronomers had observed.

“The two black holes had to be spinning fast,” explained lead author Tousif Islam, a postdoctoral scholar at UCSB’s Kavli Institute for Theoretical Physics (KITP). “And their spins had to be misaligned.”

The authors calculated that the heavier of the pair must’ve been spinning at 70–75% of the maximum allowed by general relativity, with its rotation tilted and precessing like a wobbling top. “I was initially surprised by how extreme this sounds,” Venumadhav said, “but then I realized it probably had to be the case in order to have produced the dramatic feature visible in telescopes.”

This spectacular setup tells us more about the galaxy these black holes inhabited. Or should we say galaxies?

The bigger picture

Enormous black holes appear to have developed relatively early in the history of the cosmos. But by the time the parents of RBH-1 met more than 7.5 billion years ago, neighboring super-massive black holes would’ve consolidated, leaving a single behemoth at the center of each galaxy. So this pair wouldn't have encountered each other unless their home galaxies themselves collided.

And based on the spins of the initial black holes, Islam, Venumadhav and co-author Digvijay Wadekar of UT Austin concluded that the rotation of these galaxies was likely misaligned as well. They also calculated the mass ratio, finding the bigger galaxy was at most four times larger than the smaller one.

The resulting galaxy, called GX in the paper, still shows some signs of its previous shakeup. "It doesn't look like it has settled down 100%," Islam said, "but it has settled down quite a lot." By the time two black holes merged, GX had already regrouped into a relatively cohesive whole over the course of 70 million years.

Looking to the future by looking at the past

The study emerged from collaborations during a long-term program at KITP. "We benefitted from talking to astronomers from all over the world who had come there to participate," Islam said. The results will now inform future work at the interface between gravitational wave astrophysics and galaxy mergers.

General relativity predicts that 5–10% of these mergers should give the resultant black hole a large kick, but this is the first time scientists have seen an object that fits the bill. Astronomers only recognized RBH-1 as one of these runaway black holes because they followed up the initial 2022 Hubble observation with the new James Webb Space Telescope in 2025. "Before, we did not have the technology," Islam said. "Now that we have JWST, this is hopefully the first of many such observations." And that's important for future avenues of research.

Black holes come in many different sizes, but they mainly fall into two main groups: Super-massive black holes are millions to billions of times more massive than the sun, and there's normally only one per galaxy. Meanwhile, the much more numerous stellar-mass black holes are only 20–30 times the size of the sun.

Gravitational wave observatories, like LIGO and Virgo, can tune into the signals that smaller black holes produce when they merge. "But when super-massive black holes merge, they broadcast in a much lower frequency," Islam explained.

Efforts are underway to construct a gravitational wave observatory in orbit, called LISA, which will be large enough to receive these low frequency channels. Observing more of these fast-moving objects from super-massive mergers with the James Webb Space Telescope will provide scientists with a better understanding of these phenomena. “This connects what telescopes see to what LISA will hear,” Venumadhav said.

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