UNSEEN COMPANIONS

by Ken Croswell

The vast majority of black holes elude detection. Gaia has recently found three of these invisible objects and will soon discover more.

The first black hole ever found, Cygnus X-1, epitomizes the standard view of a stellar-mass black hole: Gas from an orbiting star spirals around the dark object and heats up dramatically, emitting a plethora of X-rays. This powerful radiation is the black hole's "siren song" in the words of the Canadian rock band Rush, which in 1977 wrote a 10-minute song about a journey to Cygnus X-1.

But for every black hole that boldly broadcasts its presence via X-rays, countless others keep things on the down-low. In fact, the entire Milky Way Galaxy has only an estimated 1,000 black holes like Cygnus X-1 — versus roughly 100 million X-ray-quiet black holes.

Now the European Space Agency's Gaia spacecraft is starting to find the quiet ones. "Gaia is a total game-changer," says Kareem El-Badry (Caltech), whose team recently used the spacecraft to locate two previously unknown black holes in our galaxy. Launched in 2013 to measure the distances and motions of luminous stars, Gaia isn't the first to find a quiet black hole, but El-Badry estimates the spacecraft will eventually uncover dozens more.

"It's wonderful that we have a new population [of black holes] detected by a completely new method," says Avi Loeb (Harvard University), who was not involved in the recent discoveries. "The precision is quite remarkable."

Indeed: Observations published in the January 2024 *Publications of the Astronomical Society of the Pacific* nailed down the mass of Gaia's first black hole to about 1% — far better than the mass determination of any other stellar-mass black hole in the universe.

Such precision results from the spacecraft's exquisite measurements coupled with the work of Johannes Kepler four centuries ago. Although his three laws originally pertained to the planets orbiting the Sun, they also describe how one star orbits another — even if one of them is a black hole.

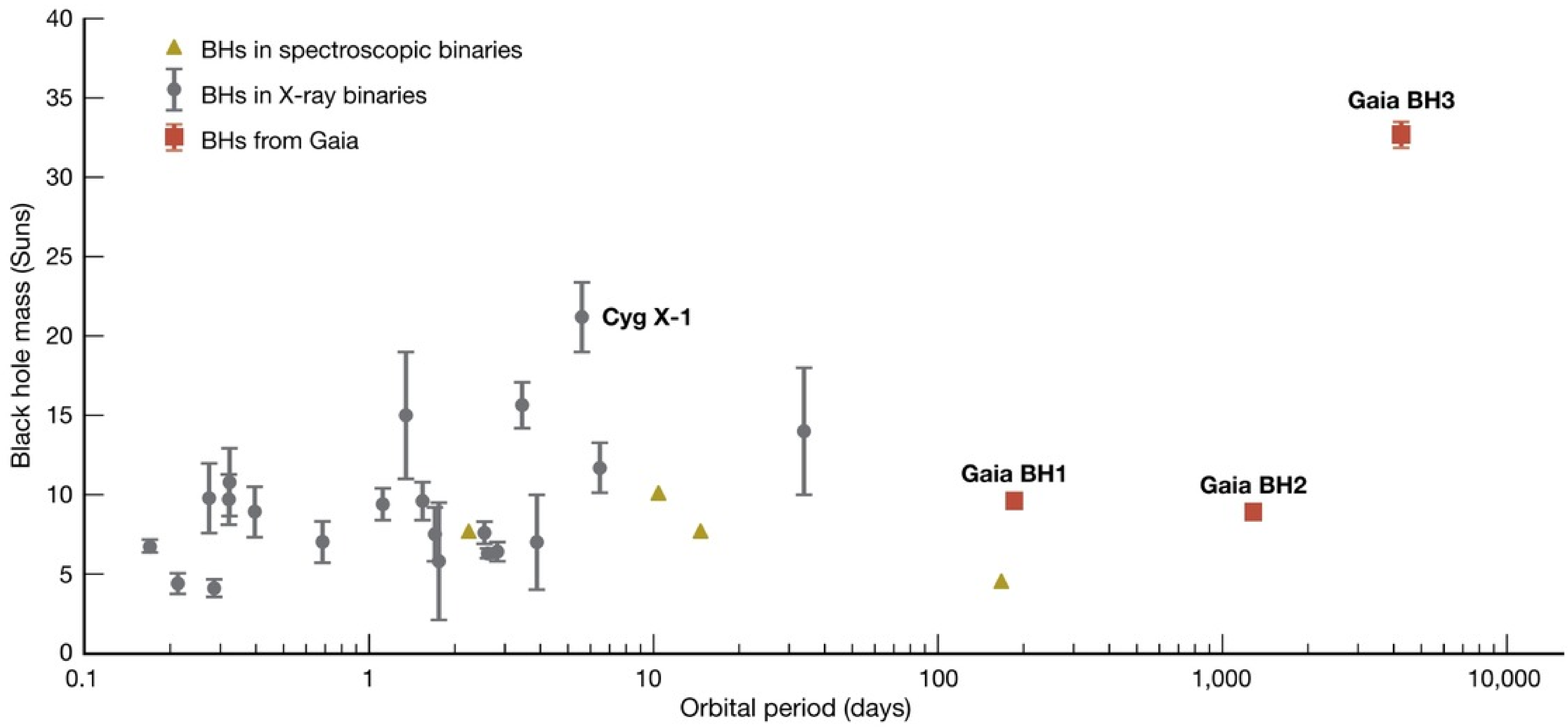
In particular, Kepler's third law allows astronomers to measure stellar masses. It states that the greater the combined mass of the two stars, the faster they whip around each other for a given separation. Measuring their orbital period and mean separation therefore reveals their total mass.

If a luminous star orbits a black hole, the star appears to be going around nothing at all. By measuring the star's changing position on the plane of the sky, Gaia sees this orbit projected onto that plane. Meanwhile, ground-based observations of the Doppler shifts in the luminous star's spectrum reveal the star's motion along our line of sight (its *radial*

▶ **GAIA'S FIRST BLACK HOLE** This visualization shows Gaia BH1 with its companion, a yellow main-sequence star. The black hole warps nearby space, causing light rays that pass through the space to bend around the black hole's location.

GAIA SKY / ESA / MPL 2.0

Gaia Begins a Black Hole REVOLUTION



▲ **GAIA OUTLIERS** Based on their masses and the orbital periods of their stars, the three Gaia black holes (red squares) stand out from other black holes that astronomers have found in binary systems. Black holes in X-ray binaries reveal themselves by the radiation from the gas they're accreting from their neighboring stars. Spectroscopic binaries are those in which the members are too far apart for the black hole to accrete gas; they're only detectable by the star's changing radial velocity.

velocity), which is perpendicular to the plane of the sky. Thus, astronomers know the exact tilt of the binary's orbit in space — necessary for a mass measurement — and can ascertain the black hole's precise mass.

This measurement enables them to determine whether the dark object is actually a black hole. A black hole forms when a massive star dies. The death may occur as the star explodes in a supernova, or the explosion may fail, in which case the star simply *im*plodes. Most supernova explosions leave behind neutron stars rather than black holes, but neutron stars can have no more than about 3 solar masses. So if Gaia and Kepler's third law reveal a luminous star orbiting a dark object that exceeds this mass threshold, the object must be a black hole.

Gaia BH1: The Black Hole Versus the Blizzard

On June 13, 2022, when Gaia scientists put out the spacecraft's third data release, El-Badry and his colleagues already had telescopes lined up in both the Northern and Southern Hemispheres to track any luminous star that seemed to be orbiting an invisible object.

But Gaia observes more than 1 billion stars. "Even if the data are very good, you expect things to go wrong in some cases," El-Badry says. "And so when you're looking for something rare, you usually assume that most will be dominated by false positives." In fact, one by one, most of the few suspicious objects in the Gaia data proved to be nothing special.

At first that also seemed to be true for a yellow sun in the constellation Ophiuchus bearing the unmemorable name Gaia DR3 4373465352415301632. The star shines between the Local Arm and the Sagittarius Arm, the next spiral arm toward the galactic center from our own.

The Gaia data suggested the star was going around something dark every half a year. "Initially we thought there was a very good chance it's wrong," El-Badry says, because a period that's an exact fraction of an Earth year could arise from some elementary error.

As it happened, the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) in China had recorded the yellow star's radial velocity twice, in 2017 and again in 2019. Both times the velocity was similar and resembled what Gaia itself had measured for the star. "It looked like it hadn't moved very much, so we thought, 'Ah, it's probably a dud,'" El-Badry says. After all, if the star was really bound to a black hole, then the star would have to move quickly to keep from falling in. So its radial velocity should always be changing as the star zooms one way and then another in its orbit.

The Magellan Clay telescope in Chile then observed the star on July 6, 2022, finding a much higher velocity. "So then we really started to think: 'OK, maybe it's real,'" El-Badry says.

But trouble lay ahead: July in Chile is winter, and a blizzard closed down the observatory.

The next measurement, made elsewhere more than three weeks later, indicated that the star was racing around something no one could see.

"With every additional velocity measurement we got, we became more convinced that it had to be a black hole," he says. The star had fooled them because, by pure chance, it had been at nearly the same position in its orbit during each earlier observation, explaining why the velocity was about the same and why the star didn't seem to be orbiting anything.

The dark object and the yellow star are about as far apart as the Sun and Mars. But the luminous star races around its dark partner about three times faster than Mars moves. Just as Mars is much less massive than the Sun, the yellow star is much less massive than the dark object it's racing around, so the star's speed primarily reflects the dark object's great mass.

For a given separation, Kepler's third law says that the binary's total mass goes as the square of the orbital velocity. Because the yellow star is moving three times faster than Mars, the dark object must be about $3^2 = 3 \times 3 = 9$ times as massive as the Sun. Such a massive invisible object can only be a black hole. Despite the exotic partner, the star itself is a *G*-type, main-sequence star like the Sun, converting hydrogen into helium at its center.

The astronomers renamed the system Gaia BH1, the "BH" standing for "black hole." With a distance of 1,560 light-years, it is the closest known black hole to Earth. "There are probably something like a million other black holes that are even closer," El-Badry says. "They're just hard to find."

That's because the vast majority of black holes are probably single, he says, even though massive stars are usually born with at least one stellar partner. But if a massive star explodes, the supernova can cast off so much material that gravity no longer keeps the companion star in orbit, and the surviving star sails off on its own. And even if the massive star merely implodes, the collapse can kick the freshly formed black hole away from its mate, because the implosion is usually asymmetric.

Meanwhile, El-Badry's team was on the trail of a second black hole. This time the obstacle was not snow but sun — or rather, *the* Sun.

Gaia BH2: The Black Hole Versus the Sun

The second black hole also has 9 solar masses. But its companion is an orange giant like Pollux, the brightest star in Gemini, rather than a yellow main-sequence star like the Sun. The binary is 3,800 light-years from Earth in the Milky Way's Sagittarius Arm.

The orange star shines in the southern constellation Centaurus, which the Sun blots out for several months every year. El-Badry's team managed to observe the star just once, on August 22, 2022, before the Sun intruded. For the next three months, the Sun blocked the view. By the time the star re-emerged, it was early December.

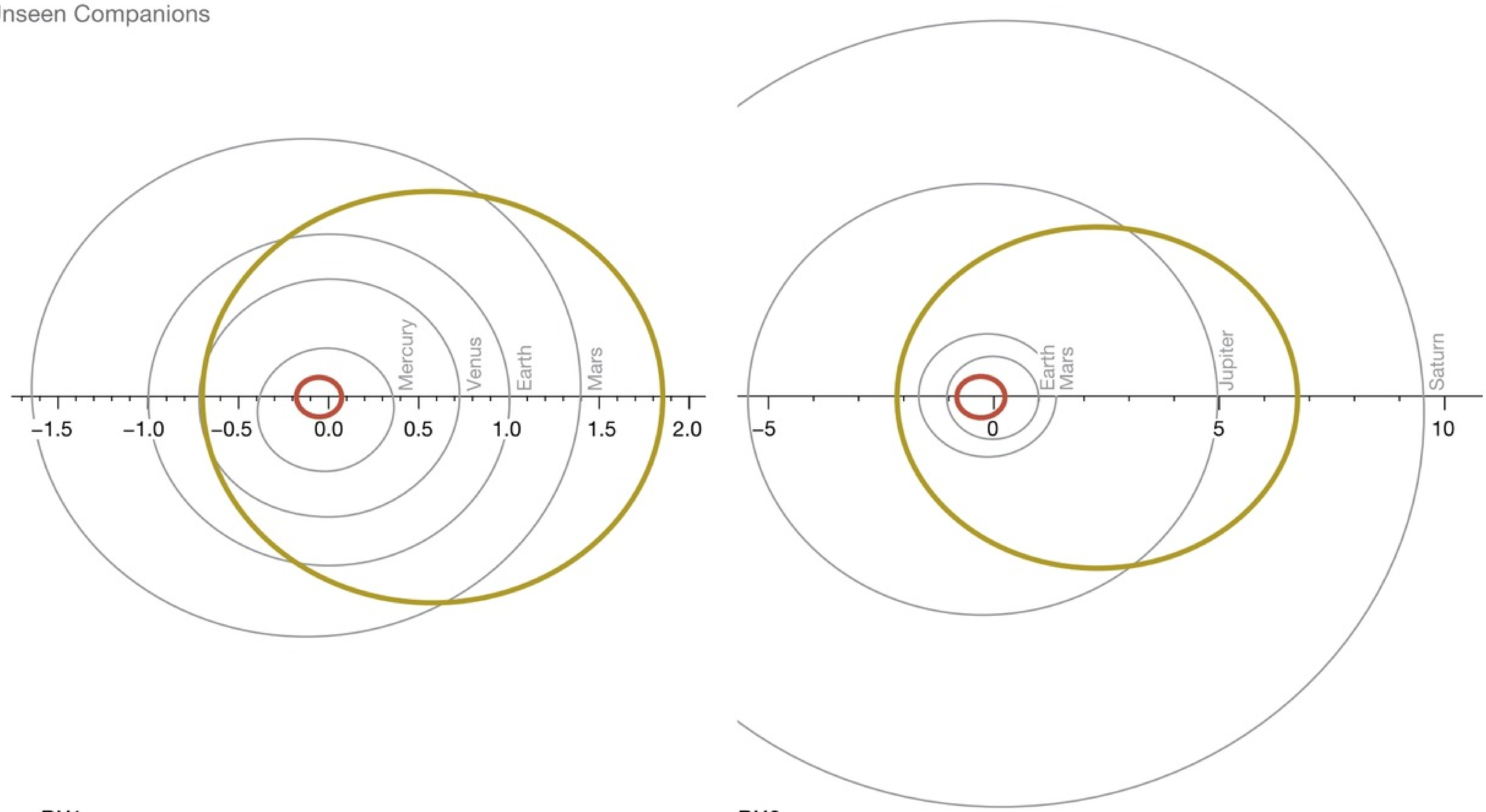
"We were lucky," El-Badry says. The star happened to be near its closest point to the black hole and so was moving fastest, à la Kepler's second law. The star's radial velocity therefore changed measurably every night, quickly confirming the Gaia orbit. The astronomers announced the discovery in early 2023. Since then, he says, "the star continues to do what Gaia says it will."

In X-ray-emitting binaries, the black hole and luminous star must be close together so that gas can spill from one to the other. Gaia-detected black holes are exactly the opposite: The two partners must be so far apart that the luminous star traces out an orbit large enough for Gaia to see the star's motion. In Gaia BH2, the black hole and orange giant are as far apart as the Sun and Jupiter. But whereas Jupiter requires 12 years to orbit the Sun, the black hole's great gravity forces the orange giant to revolve around it in just 3.5 years.

El-Badry says that 100 million years ago, Gaia BH2 resembled Gaia BH1, because the giant was then a main-sequence star. The giant is about as massive as the Sun and so was spectral type *F* or *G* while on the main sequence. Even

Black Hole Data

	Gaia BH1	Gaia BH2	Gaia BH3
Gaia DR3 Name	4373465352415301632	5870569352746779008	4318465066420528000
Constellation	Ophiuchus	Centaurus	Aquila
Distance (light-years)	1,560	3,800	1,930
Black hole mass (Suns)	9.3	8.9	33
Companion star mass (Suns)	0.93	1.1	0.76
Companion star type	Yellow main-sequence	Orange giant	Yellow giant
Star diameter (Suns)	1	8	5
Orbital period	185 days	3.5 years	11.6 years
Mean separation (au)	1.4	5.0	16.5
Orbital eccentricity	0.43	0.52	0.73
Iron abundance	65% solar	60% solar	0.3% solar
Population	Thin disk	Thin disk	Halo
Superlative	Nearest known black hole	Farthest Gaia black hole	Widest binary orbit with a stellar-mass black hole



BH1

BH2

now the giant is fairly small as such stars go, with a diameter only 8 times the Sun's, indicating that the star has not yet expanded much.

But the star does have one quirk: a large amount of what astronomers call *alpha elements*, such as oxygen, magnesium, and silicon. The star isn't massive enough to have forged these elements itself — such elements are created in massive stars (like the one that made the black hole) and shoot into space when the stars explode. However, the system's orbit is wide enough that the star shouldn't have intercepted much supernova ejecta when its companion collapsed into a black hole.

Perhaps the supernova spewed material in a jet that happened to hit the surviving star. Or perhaps the alpha-rich material whirled around the system and eventually settled onto the star.

A Black Hole Mass Gap?

The first two Gaia black holes are remarkably similar, each with 9 solar masses. Furthermore, Gaia has had no problem finding new white dwarf stars and neutron stars with much lower masses, between 1 and 2 solar masses, orbiting other stars. But the spacecraft has failed to detect any dark companions between 2 and 9 solar masses.

"That's suggestive," Loeb says, and El-Badry agrees. Perhaps most stellar-mass black holes are about 9 times as massive as the Sun, and the lowest-mass black holes are rare. Black holes in X-ray-emitting binaries as well as black-hole binaries that merge into single black holes also point to a possible paucity of the smallest black holes (*S&T:* June 2022, p. 12). But both scientists note the obvious: Two Gaia-detected black holes hardly constitute a large sample.

Both black holes share another trait. They belong to the Milky Way's *thin disk* population, which includes the Sun and most of its neighbors. Thin-disk stars shine near the galaxy's plane and range in age from stellar newborns to stars some 8 billion years old (*S&T:* Aug. 2023, p. 34).

But the third black hole system, Gaia BH3, is radically different. It's the first black hole ever found in the galactic halo and the largest known stellar-mass black hole in the galaxy.

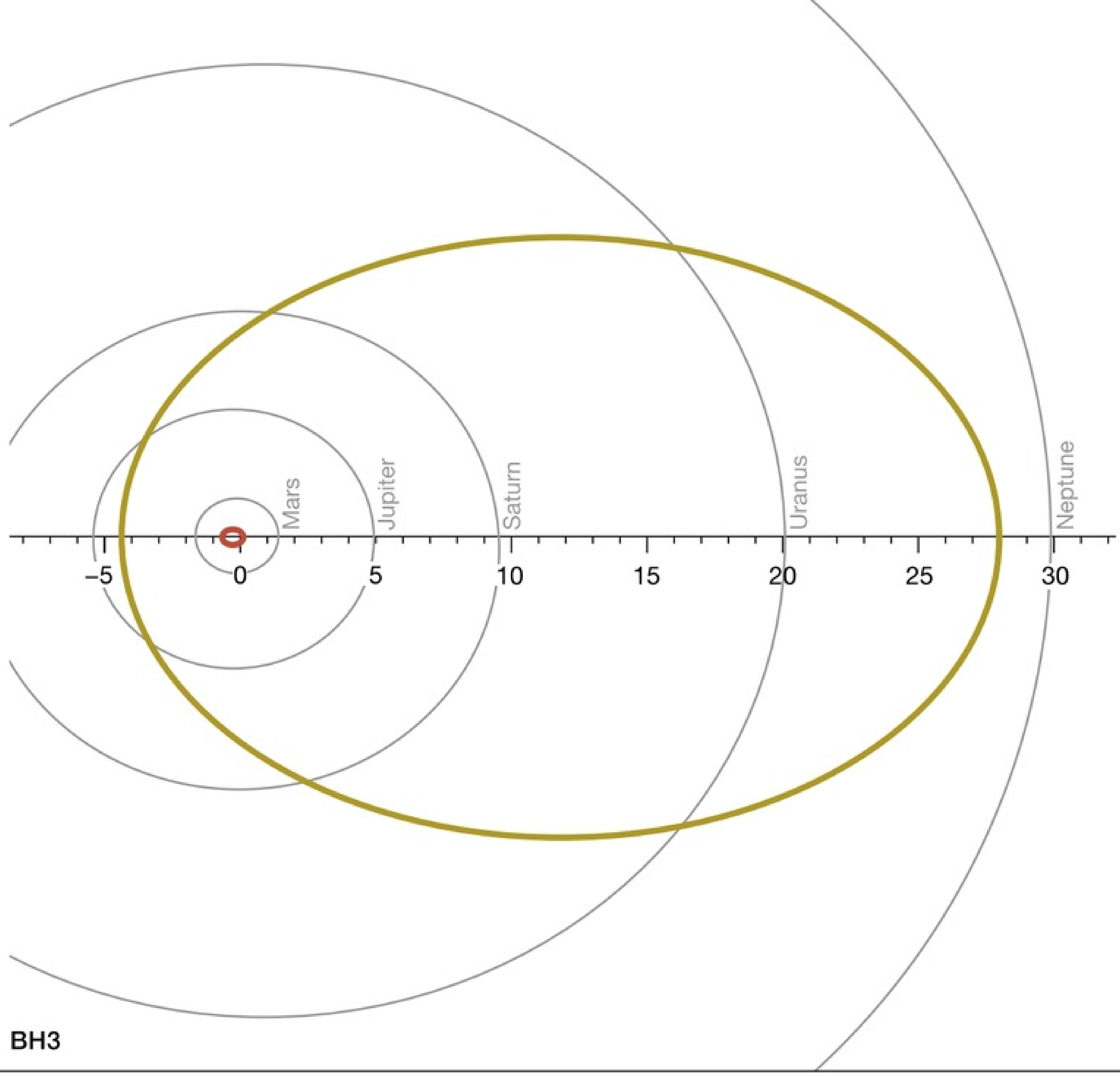
Gaia BH3: From the Edge of Time

In July 2023, Pasquale Panuzzo (Paris Observatory) was examining unreleased Gaia data. He was looking at what he calls "binary fake solutions" — stars that seemed to be orbiting massive dark objects only because of undetected errors.

But one of the fakes wasn't fake at all. "This one was real," he says. "And then we realized that it was the largest stellar black hole." Its mass — 33 times that of the Sun — easily tops the 21 solar masses of the galaxy's previous champ, Cygnus X-1. A yellow giant star orbits the black hole every

ALPHA ELEMENT

A chemical element with an even atomic number that arises mostly in short-lived, massive stars: oxygen, neon, magnesium, silicon, sulfur, argon, calcium, and titanium. Astronomers call them alpha elements because the dominant isotopes of all but titanium consist of stuck-together helium-4 nuclei, which are also known as *alpha particles*.



NEIGHBORS The stars and black holes of the three Gaia systems have separations comparable to orbits in the solar system. These distances are too far apart for the black holes to siphon gas from their companion stars. The black hole and star orbit around their common center of mass, but because the black hole is more massive than the star, it traces a much smaller circuit. Distances are in astronomical units.

Star orbit
Black Hole orbit

11.6 years. On average the two are slightly closer together than are the Sun and Uranus, according to work published in the June 2024 *Astronomy and Astrophysics*.

Located in the constellation Aquila, Gaia BH3 is plunging through the Milky Way's disk from the *halo*, the vast region of ancient stars that surrounds our galaxy's disk like a cloud. Gaia BH3 goes around the galaxy's center backward, opposite the direction of the Sun, which marks the system as a halo member. So, too, does the yellow giant's dearth of heavier elements. Its iron-to-hydrogen ratio is only 0.3% that of the Sun — low even by halo standards. That indicates the star formed long ago, before other stars had much time to enrich space with metals.

"This gives us a hint that these very massive stellar-mass black holes were made early in the universe," Loeb says. The first black hole merger, detected in 2015, astonished astronomers because its black holes were so large, bearing 36 and 31 solar masses — similar to the 33-solar-mass black hole in Gaia BH3. Loeb suspects that the merged black hole system belongs to the halo of its galaxy, too.

Says Panuzzo, "We have — finally — an equivalent in our galaxy that we can study, because it's so nearby." Gaia BH3's distance from Earth is 1,930 light-years.

Low metallicity explains how the galactic halo can hatch such a heavy black hole — for two reasons. First, metal-poor gas can spawn especially large stars. Second, metal-poor stars have weaker winds than their metal-rich counterparts and therefore lose less mass during their lives. So it's not surprising that some halo stars could form a black hole as massive as the one in Gaia BH3.

Coming Gravitational Attractions

The new discovery occurred because Panuzzo was working on Gaia's fourth data release, due out in 2026. El-Badry predicts this release will yield dozens of quiet black holes. Most will probably be in the Milky Way's disk, but some may belong to the halo. Their masses will be especially intriguing.

Meanwhile, astronomers ponder the chief mystery that the Gaia black holes pose: How did the companion star manage to survive the drama that preceded the black hole's birth? Late in life, the massive star that became the black hole should have swollen into a red supergiant like Antares or Betelgeuse, engulfing its partner. Yet the partner endures.

Theories abound. Perhaps the massive star blew away its envelope, staying blue and compact, and never became a red supergiant, so it never swallowed its companion. Or perhaps the black hole and companion originally formed in separate binaries inside a star cluster, then exchanged partners and paired up at their current separation. Although the star cluster later dispersed, the couple survives. Gaia BH3 even belongs to a stellar stream, named ED-2, which is the likely remnant of a small globular star cluster that disintegrated.

The Gaia spacecraft is clearly revolutionizing our study of stellar-mass black holes in the Milky Way. With dozens of new black hole discoveries on the horizon, the future looks bright for astronomers who seek the universe's darkest objects.

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