How to Find a Black Hole

First look for a distinctive x-ray signature, then try to measure its mass, say observers. That strategy has yielded the best black hole candidate yet

IN THE CONSTELLATION CYGNUS, THE SUpergiant star HDE22686 traces out endless circles as if under the spell of some unseen phantom. Scientists suspect that the star is caught in the gravitational grip of a ghostly companion—a surfaceless, substanceless black hole. If current physics is right, thousands more of these mysterious objects—the collapsed remains of long-dead stars—haunt our galaxy. And a few intrepid astronomers are determined to find them.

The search won't be easy. By definition, black holes themselves can't be seen. At a distance of a few kilometers or so from their centers, light-trapping gravity forms a cloak that forever conceals everything inside from curious observers. Astronomers try to see a black hole the way they would watch the wind—by observing objects it moves. With powerful ground-based telescopes and instruments aboard satellites and balloons, black hole hunters have been gathering signals from stars, gas, and dust whirling and jostling in the grasp of invisible masses. The data are now pouring in, and last month a group of about 80 astrophysicists convened at the Aspen Center for Astrophysics to sift through their harvest. "There has been a remarkable series of discoveries in the last year," says Harvard astrophysicist Jonathan Grindlay, who organized the conference.

The black holes researchers are seeking are not the monsters packing the mass of millions of stars that are thought to lurk at the hearts of some galaxies. Instead the Aspen Winter Astrophysics Conference brought together astronomers searching for the garden-variety black holes that form—so says Einstein's theory of general relativity—when a sufficiently massive star collapses at the end of its life. A major topic of discussion was a new set of criteria, based on a peculiar pattern of x-ray emissions, that appears to distinguish possible black holes from more mundane rivals. And there was considerable excitement when a team of astronomers from the Royal Greenwich Observatory in England announced that they have discovered a candidate black hole with the help of the new criteria. Known as V404 Cygni, it is hands down the most convincing black hole candidate yet.

The great hope among the crowd at Aspen was that the new criteria will help them eliminate neutron stars—compact, superdense chunks of matter—as a confounding factor in their search. The problem, say members of the Aspen workshop, has been that both neutron stars and black holes generate powerful x-rays and gamma rays from an "accretion disk"—a thick ring of gas, generally stolen from a companion star, that is slowly surrendering to the object's gravitational appetite. As material accumulates in an accretion disk, it heats up, emitting radiation. And up to now observers have not been able to identify any pattern that might distinguish the radiation coming from a neutron star's accretion disk from that coming from a black hole.

The mass of V404 Cygni has to be at least six times the mass of the sun—or twice the black hole requirement.

To be sure, neutron stars often have other features that leave little doubt about their identity. "Neutron stars have many diagnostic characteristics," says Harvard astrophysicist Jeffrey McClintock. They rotate fast, often giving off regular radio pulses. They have hard surfaces upon which infalling material can explode, sending out identifiable x-ray "bursts," and they have magnetic fields that give rise to periodic or "quasi-periodic" variations in intensity. But the lack of these signs isn't sufficient to rule out a neutron star. Worse, black holes had not seemed to have any distinguishing features of their own. For one thing, says McClintock. "There is no surface," where telltale phenomena could take place.

In fact, only one observable feature, mass, can really set black holes apart from neutron stars. No neutron star can have a mass of more than about three times that of the sun; throw another handful of matter onto a neutron star of that size, says Clemson College theorist Donald Clayton, and you'll start a runaway collapse into a black hole. "If you look at general relativity and the properties of nuclear particles, you find that there is a limit past which the pressure holding the star up can never become great enough. Nothing can stop its collapse." If a collapsed object has a mass above that limit, it becomes a black hole candidate.

But even mass isn't always definitive, since there is no hope of weighing a black hole candidate directly. Observers can get an indirect indication of mass by measuring the velocity of a companion star in orbit around the object. But the result is subject to assumptions about the mass of the companion: The lighter it is, the less mass the central object needs to hold it in orbit. That's why all the black hole candidates to date—x-ray-emitting objects that seemed to weigh too much to be neutron stars—are just that, candidates.

Take the ghost object in Cygnus that is causing HDE22686 to go around in circles. Known as Cygnus X-1, it was the first black hole candidate and, until V404 Cygni, the leading one. It was discovered in 1972, and the motion of its companion star soon led astronomers to infer that the object had 16 times the mass of the sun—far more than a neutron star could wield. But no one can prove that mass conclusively. There is a chance, say astronomers, that they have grossly overestimated the mass of the companion star—it could be just a puffy, abnormally bright thing that wouldn't take a lot of power to move through its orbit. If so, then the mystery object's mass could fall below the black hole limit.

Similar doubts plague the only other candidates generally accepted up until the Aspen meeting: LMC X-3, which under the most conservative estimates might still fall below the black hole mass threshold, and A0620, with a lower mass limit that is poised right at the threshold. But at the meeting, astronomer Philip Charles of the Royal Greenwich Observatory announced a new candidate that seems immune to such challenges.

Charles' contender, V404 Cygni, first made its presence—though not its identity—known in an intense burst of x-rays detected by the Japanese x-ray satellite Ginga in 1989. The burst was of such incredible luminosity that Charles says he knew he should study the source further. When the excitement quieted down enough for more careful study, Charles and colleagues monitored the movements of a companion star using the powerful UK/Spanish/Dutch telescopes at La Palma in the Canary Islands. This companion was orbiting so fast that even if it was made of cotton candy—even if it weighed nothing—the mystery object that had the companion star in its gravitational clutches had to have at least six times the mass of the sun, or twice the black hole requirement. "This is the best candidate so far because you don't have to make any assumptions about the mass of the companion," Charles says. He believes a more realistic mass estimate would fall between 8 and 15 solar masses. (These findings will be published by *Nature*.)

EDISON LIANG

Voracious eater. *A tiny black hole steals matter from a giant companion star, gathers it into a hot, x-ray emitting disk, and slowly swallows it.*

Charles and his colleagues were not entirely surprised to unmask a black hole as the source of the intense burst of x-rays picked up by Ginga. They had noted a suggestive pattern in the source's x-ray emissions that set it apart from hundreds of other x-ray emitters in the sky—a pattern that observers at the Aspen conference now believe may be a kind of black hole fingerprint. The pattern, the observers say, shows up consistently in the x-ray spectra of the strong black hole candidates—and not in those of neutron stars.

At first glance, making sense of the x-rays from either kind of object seems a daunting task: The emissions flare up and fade randomly, over periods of seconds to years. But in the black hole candidates, a common pattern looms behind the noise: a huge flux of "soft" (low-energy) x-rays that trails off into a more energetic "hard" x-ray tail running up into the gamma ray range. That pattern is sometimes punctuated by a spectral line right at the energy—511 kiloelectron volts—given off when electrons meet and annihilate their antimatter counterparts, positrons. The 511-kev line has a frustrating tendency to appear for a few days and then vanish, perhaps for years, so it has been observed only for some of the main suspect sources.

That's the pattern—minus the 511-kev line—that Charles and his colleagues saw in Ginga's x-ray spectra of V404 Cygni. Or, rather, they inferred it: Charles says V404 Cygni displays only the hard x-ray tail, but he believes a heavy cloud of dust and gas is obscuring the soft part. In any case, the parallel was close enough to spur him and his colleagues to go on and measure the object's mass.

Now that black hole searchers know what to look for, the x-ray fingerprint is starting to show up in new places. Yale astronomer Charles Bailyn says another x-ray emitting object, Nova Musca, shows "the same characteristic spectrum as A0620 and V404 Cygni," and the elusive 511-kev annihilation feature to boot. Bailyn plans to try to determine the mass of Nova Musca next spring, using the Cerro Tololo Observatory in Chile—and he'll be in a race with several other groups also hoping to add Nova Musca to the list of black hole candidates.

But even as astronomers put these new patterns to work in their black hole search, they are groping for some way to explain them. "The question in my mind," says Bailyn, is, "Why does the absence of a surface change the spectra in such a way that it gives you soft x-rays with a hard x-ray tail?"

So far, theorists are at a loss for an answer; indeed, they don't see why the same spectral pattern couldn't in theory emanate from a neutron star. "By the end of the week we were still convinced these features are consistent but not unique to black holes," says Grindlay. For now, the best theoretical models of radiation production around black holes and neutron stars explain only shades of difference, says Rice University theorist Edison Liang—the larger proportion of gamma radiation seen from suspected black holes, for example. "At this point the differences are quantitative and not qualitative," he says.

A theoretical model explaining why the radiation from a black hole should be unique would bolster observers' confidence that they are seeing a true black hole signature. It might also turn the observed x-rays and gamma rays into probes of what goes on right near the one-way gates of a black hole. As theorist Craig Wheeler of the University of Texas, Austin, puts it, "The x-rays and gammas can probe right down to the inside, where the guts are."

And the ability to interpret those signals might lead observers closer to what, for some of them, is the ultimate goal: direct evidence that black holes actually exist. Mass measurements, after all, tell you only that the object in question should have collapsed into a black hole—if general relativity is right. But McClintock and many of his colleagues point out that the theory has never been tested in gravitational fields anything like those near a black hole, a million times stronger than astrophysicists have ever probed. "How will we ever know if relativity holds" under those circumstances, McClintock asks, unless we can confirm the existence of black holes.

Other black hole hunters have fewer doubts about the existence of their quarry. "Saying something [with enough mass] is a black hole is the most conservative assumption you can make," says Stanford physicist Roger Romani. "You have to be a radical to say it's something else other than a black hole." Grindlay agrees: "I think there is nothing terribly remarkable about black holes."

But McClintock finds it hard to keep his mind off the outlandish quality of the objects he is pursuing. Physicists now say that the matter in a black hole collapses to a point measuring 10^{-33} centimeters across, he says. Hunting for black holes, for him, is really an exploration of the far edges of the comprehensible universe. "The idea that a black hole collapses to 10^{-33} centimeters is preposterous," he says, "but that's what makes it so exciting." ■ FAYE FLAM