BLACK HOLES in our backyard

Black holes are the most astounding objects in the universe. And at least 19 of them lurk within the Milky Way. **by Richard Talcott**

The black hole in Cygnus X-1 rips material from its supergiant companion in this artist's concept. Most of the captured gas forms a broad, million-degree accretion disk, but magnetic fields channel some of it into high-speed jets. NASA/CXC/M. Weiss

Until Swiss astronomers Michel Mayor and Didier Queloz discovered the first planet orbiting a Sun-like star in 1995, scientists faced a dilemma: They *thought* such planets should be common, but they had no *proof*. Fast-forward 17 years and the verdict is in — the number of confirmed exoplanets now totals several hundred and should pass the 1,000 mark in the next year or two.

The discovery of black holes followed a similar trajectory. By the early 1990s, most astronomers suspected these bizarre objects existed, but confirmation was hard to come by. Scientists like to say that extraordinary claims require extraordinary proof, and things don't get much more astonishing than black holes. These bodies possess a gravitational pull so powerful that nothing, not even light, can escape their clutches. Information about what happens inside a black hole can never leave — a cosmic equivalent to Las Vegas.

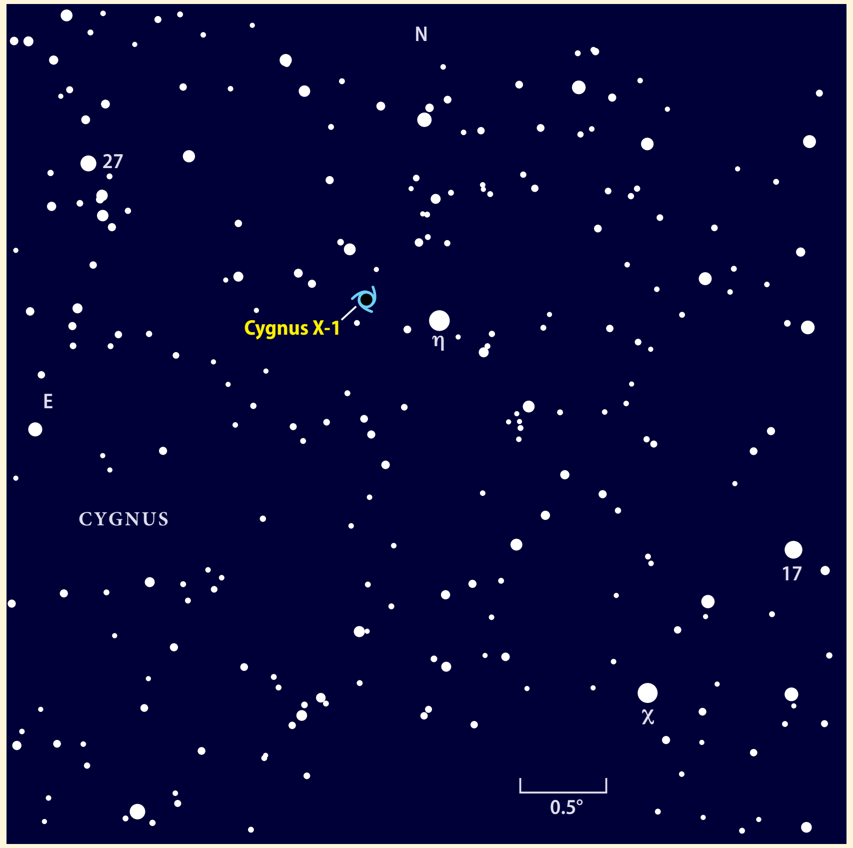
Fortunately, the suburbs of Vegas are more forgiving. Material in a black hole's vicinity suffers conspicuously from the intense gravity. Wayward stars move abnormally fast, and gas becomes superheated and radiates copious amounts of light. Astronomers confirm a black hole's existence when they see these signatures and can eliminate all other possible causes. In the past 15 years or so, the tally of black holes in our galaxy has reached 19 — 18 reside in X-ray-emitting binary star systems, and one lurks in the Milky Way's core. But many more likely remain beyond astronomers' current reach.

From Newton to Einstein

In the late 1700s, British professor John Michell and French astronomer and mathematician Pierre-Simon Laplace advanced the idea of what Laplace called "dark bodies." Using Isaac Newton's concepts of light and gravity, they reasoned that the gravitational pull of a massive star could be large enough to prevent light from escaping.

Unfortunately, Newton's theory could not describe what happens when gravity grows this strong. That understanding wouldn't come until Albert Einstein developed his general theory of relativity in the 1910s. Relativity, which treats gravity as a distortion of space-time, allows physicists to describe black holes in gory detail. Still, it took decades before most scientists considered these objects more than theoretical curiosities.

The reality of black holes began to emerge once astronomers understood how massive stars die. If a star begins life with more than about eight times the Sun's mass, it will not experience a quiet demise. When such a star exhausts its nuclear fuel, its core collapses. This triggers a shock wave that destroys the rest of the star in a



The relatively nearby black hole Cygnus X-1 has a 9th-magnitude blue supergiant companion that shines brightly enough to show up through amateur telescopes. You can find it 0.4° east-northeast of the 4th-magnitude star Eta (η) Cygni. *Astronomy*: Roen Kelly

Track down a black hole

By definition, black holes give off no light. This makes the idea of trying to see one sound a bit challenging. Fortunately, black holes don't always live in isolation, and one of the most famous — Cygnus X-1 — has a partner that shows up through any backyard instrument.

Cygnus X-1's stellar companion is a blue supergiant cataloged as SAO 69181. This star shines at magnitude 8.9 in the central regions of the constellation Cygnus the Swan, which passes nearly overhead on September evenings for observers at mid-northern latitudes.

Use the circular StarDome map at the center of this issue to locate Cygnus. Next, home in on Eta (η) Cygni, a 4th-magnitude star that lies 13° southwest of the Swan's luminary, 1st-magnitude Deneb. Scan 0.4° east-northeast of Eta to find SAO 69181. It's the middle object in a line of three equally bright stars. When you spot it, you won't be seeing light from the black hole, but it will be literally from the next closest thing. — *R. T.*

brilliant supernova that can shine with the light of 10 billion Suns. In most cases, the core left behind weighs between 1.4 and 3 solar masses and has been crushed into a sphere the size of a major city. A single teaspoonful of this so-called neutron star would weigh close to a trillion tons.

Yet even this exotic end state pales in comparison with what happens to the rarest of stars that start life with more than 30 solar masses. In 1939, physicists J. Robert Oppenheimer and Hartland Snyder showed that when such a star dies, its collapsed core (which weighs more than three Suns) is too heavy to settle down as a neutron star. It creates a region of space-time cut off from the rest of the universe because no light can ever escape. Thirty years later, physicist John Wheeler coined the descriptive term *black holes* for these objects.

Black holes possess only three characteristics: mass, spin, and charge. All other properties of the collapsing star are lost. And because stars rarely have any excess positive or negative charge, mass and spin describe most black holes.

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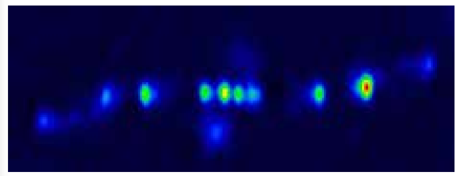
Cygnus X-1 radiates strongly in X-rays because the temperature in the black hole's accretion disk surpasses 1 million degrees. The Chandra X-ray Observatory captured this glow during a 16-hour observation. NASA/CXC/SAO



SS 433 contains a normal star orbiting a compact object, which is surrounded by an accretion disk that feeds two radio-emitting jets. Astronomers don't know if the compact object is a neutron star or a black hole. Amy Mioduszewski, et al. (NRAO/AUI/NSF)

A key feature of a black hole is its "event horizon" — the radius at which a beam of light would just fail to escape. Any event that takes place within this horizon can never be glimpsed from outside. For a nonspinning, 10-solar-mass black hole, the event horizon spans approximately 37 miles (60 kilometers). Double the mass, and the diameter also doubles. A black hole spinning at the maximum possible rate has a diameter half that of a nonrotating one with the same mass.

The galaxy's black holes

Because telescopes cannot see inside the event horizon, astronomers must search for a black hole's impact on its immediate surroundings. Some binary star systems offer a perfect environment. The massive stars that create black holes evolve quickly, typically running through their nuclear fuel in a few million years.

After the star explodes (the companion usually survives), the black hole's intense gravity may pull material from its neighbor's outer layers. This gas falls toward the black hole and forms an accretion disk that swirls around the invisible object like water circling a drain. As the material moves ever faster, friction among the atoms heats it to millions of degrees. Gas at this temperature emits lots of X-rays, which Earth-orbiting observatories can detect.

So, to detect a black hole, astronomers look for an X-ray-emitting binary system comprising one normal star and an invisible but massive companion. Lots of these objects exist in the Milky Way, but not all contain black holes. Neutron stars in a binary can produce the same behavior, and because they radiate little light, they can't be detected across large distances.

To differentiate between the two possibilities, astronomers need to pin down the compact object's mass. General relativity says that a stable neutron star can't weigh more than three Suns. Any invisible companion bigger than that must be a black hole — assuming, as almost every scientist does, that relativity accurately describes such strong gravitational fields. To find the object's mass, astronomers must measure the binary system's orbit precisely.

Ronald Remillard of the Massachusetts Institute of Technology in Cambridge and Jeffrey McClintock of the Harvard-Smithsonian Center for Astrophysics (also in Cambridge) have compiled the most up-to-date list of black holes in binary systems. Our galaxy contains 18; their locations and properties appear on page 49.

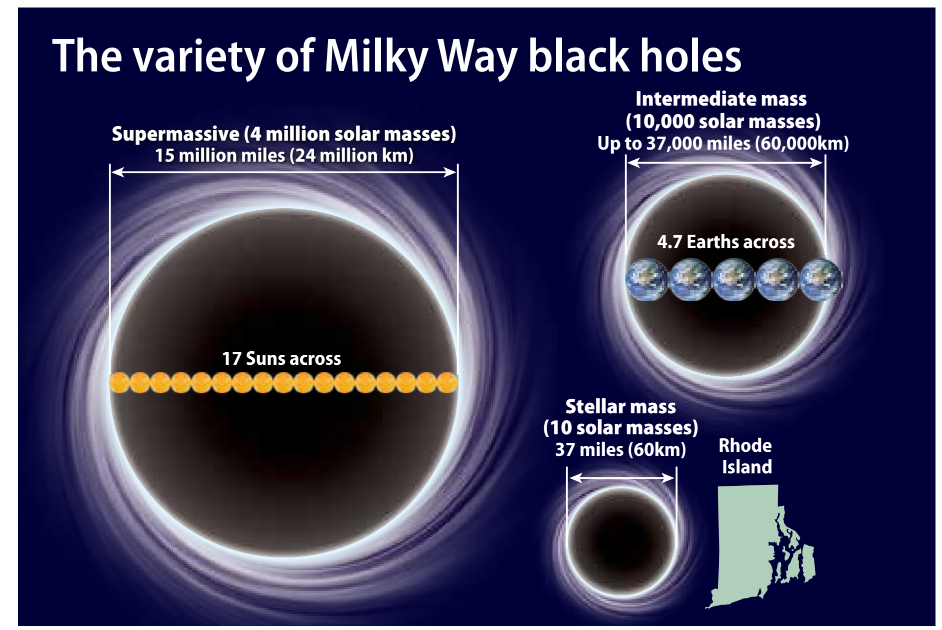
But this list likely forms only the tip of the iceberg. Remillard and McClintock count 20 more binary systems that show similar X-ray signatures but have no detailed orbital information to provide masses. (Astronomers haven't even seen an optical counterpart in most of them.) And nearly every scientist suspects far greater numbers of black holes exist either alone in space or in more widely separated binaries that don't emit X-rays. Astronomers estimate that the Milky Way holds between 100 million and 1 billion black holes.

The Swan's song

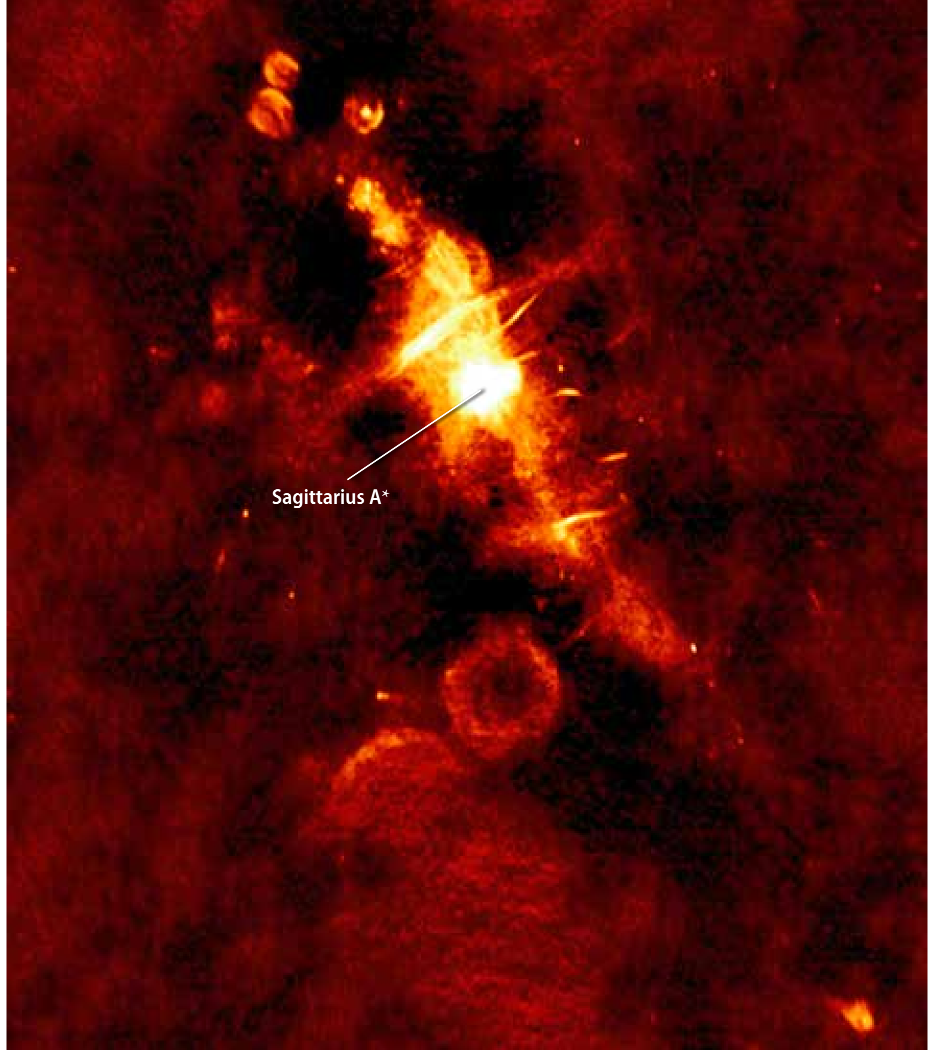
The most famous stellar-mass black hole is Cygnus X-1 (its designation signifies it as the first X-ray source discovered in Cygnus the Swan), which lies some 6,100 light-years from Earth. It is the only one in a high-mass X-ray binary system — its companion star is a blue supergiant that tips the scales at approximately 19 solar masses. In fact, this luminous companion shines brightly enough that it appears in our sky as a 9th-magnitude star visible through amateur telescopes (see "Track down a black hole" on page 46).

The black hole in Cygnus X-1 weighs close to 15 solar masses, which makes it the heaviest one known in a binary system. The two objects orbit each other once every 5.6 days at an average distance about half that between the Sun and Mercury. As matter in the accretion disk falls toward the black hole, magnetic fields channel some of it into a pair of high-speed jets that emerge perpendicular to the disk. Recent observations show that the black hole rotates at more than 90 percent of the theoretical maximum.

Globular cluster M15 may harbor a nearly 1,000-solar-mass black hole. Scientists continue to argue if M15 and other globulars contain intermediate-mass black holes. NASA/ESA/The Hubble Heritage Team (STScI/AURA)



Eighteen of the galaxy's 19 known black holes weigh between three and about 15 times the Sun's mass but have diameters the size of a small state. If intermediate-mass black holes exist, they would extend a few Earth diameters. The central supermassive black hole spans 17 Suns. *Astronomy*: Roen Kelly



The Milky Way's core contains a black hole weighing some 4 million solar masses. This supermassive object, dubbed Sagittarius A*, glows at radio wavelengths (seen here) and in X-rays but disappears in visible light because so much dust lies between Earth and the galactic center. NRAO/AUI/NSF

The other 17 stellar-mass black holes reside in low-mass X-ray binaries. Most of their companion stars have masses similar to or somewhat smaller than the Sun. Still, a few of these objects stand out. Astronomers estimate the mass of GRS 1915+105 (a designation that comes from the Russian Granat satellite and the object's sky coordinates) in Aquila at 14 Suns, but with an uncertainty of 4 solar masses, it could be the heavyweight champ. This object also spews jets that appear to travel faster than the speed of light — an optical illusion that arises because the jets move at about 90 percent light-speed toward Earth. It marked the first time scientists had seen such superluminal motion within our galaxy.

Meanwhile, GX 339-4 lies in the southern constellation Ara and experiences frequent X-ray outbursts followed by periods when its emission decreases, but never so far as to let its companion star shine through. It's the only binary black hole whose companion still eludes detection.

Just because a binary system behaves oddly doesn't mean it possesses a black hole, though. Few objects in the galaxy sport the peculiarities of the high-mass X-ray binary SS 433, which lies inside a 10,000-year-old supernova remnant called W50. The explosion that created this glowing remnant gave birth to a compact object that now steals material from a massive companion star. The gas forms an accretion disk that powers two jets beaming in opposite directions like a pair of rotating lighthouse beacons. Many astronomers think SS 433's compact object is a black hole, but they can't rule out a neutron star.

Black holes in globulars?

The biggest stellar-mass black holes in our galaxy appear to top out at about 15 to 20 times the Sun's mass. Yet a number of scientists think much larger ones exist in some of the galaxy's 150 or so globular star clusters. Star-sized black holes likely formed in these clusters early in their histories, more than 10 billion years ago, and fairly quickly sunk to the center. But what happened to these black holes? Some theorists think that they merged with other black holes or neutron stars and grew much bigger, while others suspect that they encountered other stars that then ejected them from the cluster.

Thomas Maccarone of the University of Southampton in England and his colleagues reported in 2007 on the best candidate for a black hole in any globular cluster. They found an X-ray source in a globular circling the giant elliptical galaxy M49, located some 50 million light-years away in the Virgo cluster. The object emits far too many X-rays to be a neutron star and so must be an accreting black hole. Its mass exceeds 20 Suns but could be much higher.

The case for black holes in our galaxy's globulars is more tenuous. Unless a black hole actively feeds on material from another star, it won't have an accretion disk that glows in X-rays. The best alternative method is to look at the brightnesses and motions of the stars near a cluster's center.

Several research teams have examined the Milky Way's largest globular, Omega Centauri, to do just that. In 2008, a group led by Eva Noyola of the Max Planck Institute for Extraterrestrial Physics in Germany reported a black hole weighing 40,000 solar masses. Just two years later, however, Jay Anderson and Roeland P. van der Marel of the Space Telescope Science Institute in Baltimore, Maryland, found no evidence for a black hole of that size. At this stage, neither side seems to be winning the debate.

A similar argument rages over the relatively nearby globular M15 in Pegasus. Some researchers claim the presence of an intermediate-mass black hole weighing about 4,000 Suns, while others find no such evidence. Earlier this year, Jay Strader of the Harvard-Smithsonian Center for Astrophysics and his colleagues announced that new observations show M15 can't have a black hole larger than 980 solar masses.

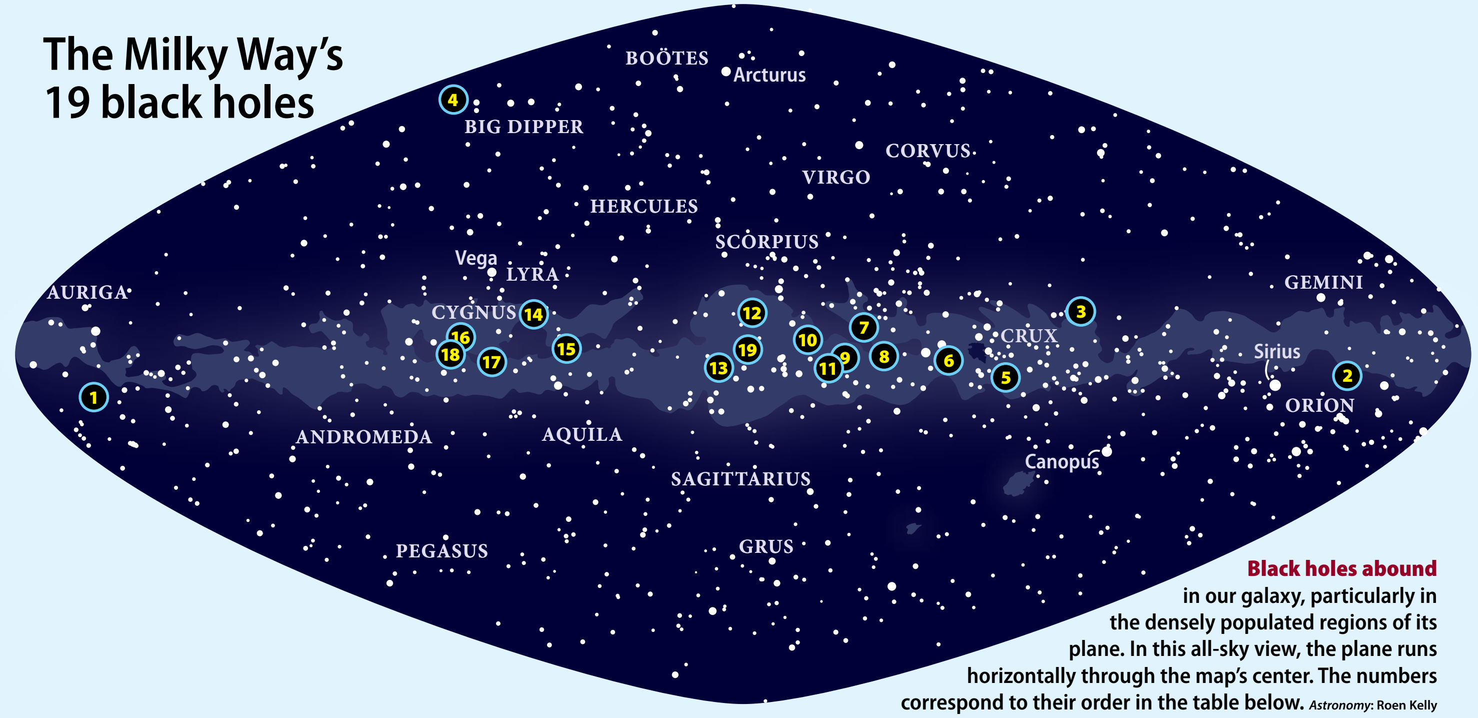
The beast in the middle

While strong evidence for intermediate-mass black holes is lacking, the same can't be said for their big brothers. Astronomers have found compelling signs for a supermassive black hole in the center of almost every large galaxy they have scrutinized, and the Milky Way is no exception. The core of our galaxy harbors an object called Sagittarius A* (pronounced A-star) — a black hole with about 4 million times the Sun's mass. It's the 19th confirmed black hole in the Milky Way, and it sits dead in the center.

The evidence takes several forms. First, intense radio waves and X-rays flow from an accretion disk that spans a region no bigger than our solar system. But the proof comes from careful tracking of the motions of stars as they orbit the central mass. It's the same method astronomers use to hunt for globular cluster black holes, but the huge size of the object in the Milky Way's heart makes these motions far easier to see. Analyzing the stellar orbits leads directly to the black hole's mass.

The count of black holes in our galaxy likely will continue to grow in the years ahead, but it never will outpace the flood of planet discoveries. The ability to find planets has reached the stage where it's surprising when a week goes by without a new detection. Black holes hide their identities much better, either behind the cloak of an event horizon or in isolation from other objects. Perhaps the biggest surprise in the study of our galaxy's black holes is that we've already found 19.

The Milky Way's 19 black holes



Black holes abound in our galaxy, particularly in the densely populated regions of its plane. In this all-sky view, the plane runs horizontally through the map's center. The numbers correspond to their order in the table below. *Astronomy*: Roen Kelly

Number	Designation	R.A.	Dec.	Constellation	Spectral type	Magnitude	Period (hrs)	Distance (lys)	Type	Mass (Suns)
1	GRO J0422+32	4h21.7m	32° 54'	Perseus	M4 V	13.2	5.1	8,000	Low-mass X-ray binary	4
2	A0620–00	6h22.7m	–0° 21'	Monoceros	K4 V	11.2	7.8	3,400	Low-mass X-ray binary	11
3	GRS 1009–45	10h13.6m	–45° 05'	Vela	K7 V	14.7	6.8	12,500	Low-mass X-ray binary	4
4	XTE J1118+480	11h18.2m	48° 02'	Ursa Major	K5 V	12.3	4.1	5,800	Low-mass X-ray binary	7
5	GRS 1124–684	11h26.4m	–68° 41'	Musca	K5 V	13.3	10.4	18,000	Low-mass X-ray binary	7
6	GS 1354–64	13h58.2m	–64° 44'	Circinus	G IV	16.9	61.1	86,000	Low-mass X-ray binary	7
7	4U 1543–475	15h47.1m	–47° 40'	Lupus	A2 V	14.9	26.8	24,500	Low-mass X-ray binary	9
8	XTE J1550–564	15h51.0m	–56° 29'	Norma	K3 III	16.6	37.0	17,300	Low-mass X-ray binary	10
9	XTE J1650–500	16h50.0m	–49° 58'	Ara	K4 V	?	7.7	8,500	Low-mass X-ray binary	4
10	GRO J1655–40	16h54.0m	–39° 51'	Scorpius	F5 IV	14.2	62.9	10,000	Low-mass X-ray binary	6
11	GX 339-4	17h02.8m	–48° 47'	Ara	?	—	42.1	20,000	Low-mass X-ray binary	at least 6
12	Nova Ophiuchi 77	17h08.2m	–25° 05'	Ophiuchus	K5 V	15.9	12.5	33,000	Low-mass X-ray binary	7
13	Sagittarius A*	17h45.7m	–29° 00'	Sagittarius	—	—	—	26,000	Supermassive	4 million
14	V4641 Sagittarii	18h19.4m	–25° 24'	Sagittarius	B9 III	9	67.6	32,000	Low-mass X-ray binary	7
15	XTE J1859+226	18h58.7m	22° 39'	Vulpecula	K0 V	15.3	6.6	20,500	Low-mass X-ray binary	5
16	GRS 1915+105	19h15.2m	10° 57'	Aquila	K III	12.2	804	39,000	Low-mass X-ray binary	14
17	Cygnus X-1	19h58.4m	35° 12'	Cygnus	O9.7 Iab	8.9	134.4	6,100	High-mass X-ray binary	15
18	GS 2000+251	20h02.8m	25° 14'	Vulpecula	K5 V	18.2	8.3	6,500	Low-mass X-ray binary	7
19	V404 Cygni	20h24.1m	33° 52'	Cygnus	K0 IV	12.7	155.3	8,000	Low-mass X-ray binary	12

R.A. = Right ascension (2000.0); Dec. = Declination (2000.0); Spectral type and Magnitude are for the black hole's companion star; Period is the orbital period of binary systems in hours; Distance is estimated in light-years; Mass is approximated in solar masses

Watch a black hole devour a star at www.Astronomy.com/toc.

NASA/CXC/MIT/F. K. Baganoff, et al.

The supermassive black hole at our galaxy's heart is not a voracious eater. This X-ray image reveals lobes of hot gas extending a dozen light-years from the black hole (Sagittarius A*) but only a small glow for the black hole itself.