The swan’s dark heart

Astronomers discovered what they thought was the first black hole more than 40 years ago but have only recently verified its identity by establishing its distance, mass and spin. These fascinating observations are yielding new insights into Cygnus X-1’s past and future, as Ken Croswell explains.

Ken Croswell is an astronomer and author in Berkeley, California, e-mail kencroswell@kencroswell.com

Who says you can’t get anything out of a black hole? In the past two years, astronomers have taken unprecedented aim at the first black hole ever found, Cygnus X-1. Using a vast armada of instruments, they have pinpointed Cygnus X-1’s distance, which has let them measure the black hole’s mass and even determine how fast it spins. These feats have then motivated two other astronomical teams to decipher the black hole’s past and forecast its future.

The flurry of recent activity concerning an object astronomers discovered nearly half a century ago has one simple cause: for the first time, we know its distance. “The distance was the breakthrough,” says Jerome Orosz, an astronomer at San Diego State University in California.

To a non-astronomer, the distance to a celestial object may seem trivial, just another arcane statistic about a far-off body. In fact, distances are as vital as they are difficult to obtain. If you do not know how far away a star is, you do not know how much light it emits, which makes estimating its mass more difficult. A star that is twice as far away as you had thought is also four times as powerful.

Furthermore, in the case of Cygnus X-1, this distance held the key to whether it really was a black hole at all. Most dead stars – dark objects that no longer shine – are not black holes. But dark objects that are at least three times as massive as the Sun must be black holes, because they are so heavy that nothing can stop them from collapsing into one. For Cygnus X-1, a 2009 paper gave such an enormous range of distances – from 3600 to 8200 light-years...
– that some of the resulting masses implied it might possibly lack a black hole.

It was in 1964 that a rocket flight first detected X-rays from Cygnus, a constellation north of the celestial equator that resembles a large cross – or a swan in flight, for “cygnus” means swan in Latin (see p36). Because the object was the first source of X-rays found in Cygnus, astronomers christened it Cygnus X-1. However, Cygnus X-1 rose to fame only in 1971 when astronomers linked the X-ray source to a massive blue star named HDE 226868. Every 5.6 days, the blue star whirled around something no-one could see. Crude estimates of the star’s distance and mass suggested its dark companion weighed so much that it was a black hole. In this picture, the blue star sheds gas, some of which spirals toward the black hole. Friction and gravity heat this gas as it forms a spinning disc of material – a so-called accretion disc – around the black hole. The gas gets so hot it emits X-rays.

But black holes are tough to study, and in 1974 Stephen Hawking even bet Caltech physicist Kip Thorne that Cygnus X-1 had no black hole at all. Instead, the dark object might be just a neutron star, fool’s gold in the quest for nature’s most extreme stars. Whereas both black holes and neutron stars are dead dense stars, black holes alone have so much surface gravity that nothing – not even light, the fastest thing in the universe – can escape their grip. Many purported black holes reported during the 1970s proved to be mere neutron stars when astronomers obtained better data.

Not everyone appeared quite so worried about Cygnus X-1’s status, and in 1977 the Canadian rock band Rush released a 10-minute song that declared Cygnus X-1 a black hole. According to the band, the six stars that make up the pattern of the Northern Cross were “in mourning for their sister’s loss”, the once brilliant star that died and became the black hole.

Astronomers, meanwhile, began to refine their estimate of Cygnus X-1’s distance, and by 1990 Thorne put the odds of its harbouring a black hole at 95%. Although he did not consider this high enough to claim his bet with Hawking, the latter later conceded defeat and fulfilled the terms of their agreement: he gave Thorne a one-year subscription to that well-known scientific journal, Penthouse.

Beyond measure?

Despite the concession, doubts lingered. How does one measure the precise distance of an object thousands of light-years away? Cygnus X-1 seemed far beyond the reach of parallax, the gold standard for determining celestial distances. Parallax refers to the slight wiggle that a star appears to have when we view it from Earth, which results because as the Earth circles the Sun, we see the star from slightly different perspectives during the course of a year. The closer
the star to Earth, the greater the parallax, and by measuring this phenomenon we know, for example, that Sirius, the brightest star in the night sky, is precisely 8.6 light-years from Earth.

Sirius is nearby, however, so its parallax is large and easy to measure. More distant stars have smaller parallaxes, and with few exceptions optical astronomers have measured no good parallaxes to objects located more than a few hundred light-years from Earth. Since Cygnus X-1 was even further still, its parallax seemed as unattainable as a transatlantic flight did to the Wright brothers.

Fortunately, Cygnus X-1 emits not only light and X-rays but radio waves as well, which arise from electrons outside the hot accretion disc. The presence of this radiation allowed astronomers using the Very Long Baseline Array, which consists of ten 25 m radio telescopes spanning North America and beyond, to measure Cygnus X-1’s position better than could any telescope on Earth or in space and thus to discern the black hole’s minuscule parallax.

Such precision was essential to determine Cygnus X-1’s great distance. “Cygnus X-1 produced beautiful data,” recalls Mark Reid of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, who led the effort to measure the parallax. “There’s no doubt about its distance now.” It is 6050 light-years from Earth, with an uncertainty of only 6% – an astonishing result for such a far-off object.

Shedding light on the dark star
Nor is there any remaining doubt about Cygnus X-1’s nature. Just as Rush proclaimed, it really does harbour a black hole. Knowing the distance, the astronomers deduced how much light the black hole’s massive blue stellar partner radiates into space as well as the star’s diameter. This information, plus the star’s orbital speed and period, led to calculations of the masses of both objects, the blue star being 19.2 times more massive than the Sun.

More crucially, the black hole is quite hefty itself: 14.8 solar masses, say the astronomers, with an uncertainty of just one solar mass (2011 ApJ 742 84). This puts the dark star well above the three-solar-mass dividing line between neutron stars and black holes. “Before our paper, the masses were all over the place,” says Orosz. “Most people, I think, would have agreed that it was a black hole; but whether a five-solar-mass black hole or 15 or somewhere in-between was sort of an open question.”

The astronomers sought more than just the black hole’s mass. “Ultimately we really wanted the spin,” says Jeffrey McClintock of the Harvard-Smithsonian Center for Astrophysics. “Spin really changes how a black hole operates, because when a black hole is spinning, there is a vast amount of energy stored in that spin.”

Exotic though black holes are, they are actually quite simple, for theory says they have only three physical properties: mass, spin and electric charge. Since positive and negative charges cancel out, astronomers presume – as they do for all large black holes – that Cygnus X-1’s black hole is electrically neutral. That means you can describe the whole thing using just two numbers. “Tell me the mass and the spin, and that’s it,” says Orosz.

However, a black hole can spin only so fast. Astronomers therefore express black-hole spins as a percentage of the maximum possible angular momentum the black hole can have. The faster a black hole rotates, the closer a particle can orbit it, and for a black hole that is spinning at top speed, the inner edge of the accretion disc is six times closer to the black hole than it would be if it were not spinning at all.

And that has an observable consequence: the closer the accretion disc is to the black hole, the hotter it gets. Lijun Gou of the National Astronomical Observatory of China, in Beijing, and colleagues therefore used X-ray spectra to determine the temperature. Cygnus X-1 accretes little mass from its partner, yet the accretion disc’s temperature is high, about 5 million kelvin. That means the accretion disc almost touches the event horizon, the black hole’s point of no return.

“It’s spinning very fast,” says Gou. “The spin is very close to maximum.” Indeed, the black hole is rotat-
ing so quickly that its angular momentum is about 99% of the maximum possible, making Cygnus X-1 one of the fastest spinning black holes known. Material at the inner edge of the accretion disc, therefore, whirls around the black hole at half the speed of light, completing 800 orbits per second.

Moreover, thanks to Einstein’s famous equation $E = mc^2$, all that spin energy counts as mass. In fact, the spin energy produces about a quarter of the black hole’s measured mass. If the black hole were not spinning, it would not have 14.8 solar masses but would weigh several solar masses less. As for why the black hole spins so fast, the astronomers think it was probably born that way. Massive stars often spin fast, and when the star that died collapsed to become the black hole, it probably spun even faster, just as spinning ice skaters do when they draw in their arms.

**Massive start, explosive end**

After the mass of both the black hole and the companion star were known, in 2011 other astronomers began to work out its history. Tsing-Wai Wong, an astronomer at Northwestern University in Illinois, and his colleagues say the system was born between 8.7 and 11.4 million years ago with two massive stars orbiting each other. The more massive star – the one that is now the black hole – was born at least 110 times heavier than the Sun, making it one of the most luminous stars in the galaxy. Its partner had less mass, he says, between 20 and 23 solar masses.

Despite their gargantuan nature, both stars generated energy as the Sun does: by using nuclear reactions to convert hydrogen into helium at their centres. In the jargon of astronomers, the two behemoths were “main-sequence” stars like the Sun, but so hot that they emitted most of their energy at ultraviolet (not visible) wavelengths and looked blue rather than yellow. Although the more massive star had more fuel, it shone much more brightly and therefore ran out of fuel faster, after less than four million years. Wong says that right before it died, the star had lost its outer envelope of hydrogen, leaving behind only a helium core having 15–20 solar masses – a fraction of the amount the star was born with. Then the star died, possibly exploding as a supernova, or perhaps collapsing without an explosion. Either way, it became the black hole we see today, weighing 14.8 solar masses.

Wong estimates that the black hole formed 4.8–7.6 million years ago and that its mass has remained roughly the same throughout its life. The companion star loses gas in all directions, with only 0.1 or 0.2% of that gas plunging into the black hole.

As for the fate of Cygnus X-1, another team of astronomers, led by Krzysztof Belczynski at the University of Warsaw in Poland, has found its future will be as interesting as its past. “We did something very simple,” Belczynski explains. “We took the system and moved it forward in time.” According to his team’s calculations, the shining star will expand, shedding more and more of its mass into space. Most of this mass will enter the galaxy at large, but some will get gobbled up by its ravenous partner. In particular, he thinks the shining star will lose about 15 solar masses and the black hole gain about three. Thus, the two will reverse roles: whereas the black hole is now the less massive object, it will wind up with 17.8 solar masses, while its partner slims down to about four solar masses.

As the shining star loses mass, it will keep dancing around its dark mate but slowly move away from it, thereby conserving angular momentum. Right now the distance between their centres is about half that from the Sun to Mercury. In 2.6 million years’ time, however, they will be slightly farther apart than the Sun is from the Earth.

The visible star will then explode as a supernova, its core collapsing into a neutron star, and probably dart away from its dark partner. Belczynski puts the odds of such a stellar divorce at 70% – because the two stars will have moved so far apart that they no longer feel each other’s gravity as strongly, and because the supernova explosion will eject material that now binds the two together. Chances are, then, they will not become a black-hole–neutron-star binary.

A binary with two dense stars intrigues physicists who hope to detect a burst of gravitational radiation when the two objects spiral together and merge. But even if Cygnus X-1 becomes a black-hole–neutron-star binary, the two dead stars will likely stay so far apart that they never merge. Indeed, astronomers have so far never discovered any black-hole–neutron-star binaries at all. Furthermore, if Cygnus X-1 is typical, Belczynski says that merging black-hole–neutron-star binaries are unlikely sources of gravitational radiation with mergers of black-hole–black-hole and neutron-star–neutron-star binaries being better bets. (For more black-hole mergers see October 2011 pp36–41.)

Such far-reaching conclusions all stem from the simple act of measuring the first accurate distance to the first black hole ever found. In fact, the new work establishing Cygnus X-1’s distance and mass has finally persuaded Thorne, the physicist who won his bet with Hawking. As Thorne recently put it, “I have never been completely convinced that it really does contain a black hole – until now.”